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## A STUDY OF RSI UNDER COMBINED STRESSES

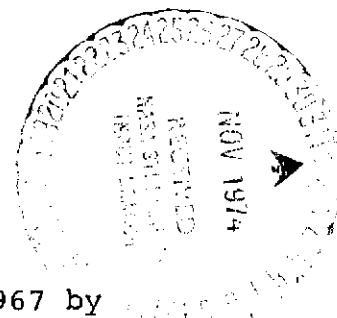
By J. J. Kibler and B. W. Rosen

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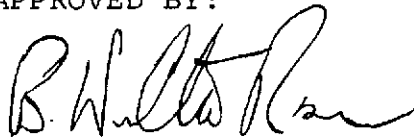
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FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HAMPTON, VIRGINIA

APPROVED BY:

A handwritten signature in dark ink, appearing to read 'B. Walter Rosen', is written over a horizontal line.

B. WALTER ROSEN, PRESIDENT

September 1974

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# SYMBOLS LIST

$A, B, C, A_i, a_i, b_i, c_i$	Constants as defined in text.
$a, b, c,$	RSI cell edge dimensions.
$e$	Eccentricity of fiber distribution
$E_i$	Young's Modulus in $i^{\text{th}}$ direction.
$f_i$	Normalized number of fiber intersections per scanning line length per orientation of scanning line on photomicrograph.
$f(\theta)$	Continuous distribution function for fiber distribution in RSI.
$g(\phi)$	Discrete fiber distribution function for representing $f(\theta)$ .
$G$	Shear modulus.
$L$	Total length of each fiber in cell.
$N, S, T$	Coordinate System for RSI tile $N$ = through-the-thickness $S, T$ = in the plane of tile.
$V$	Least squares - sum of squared residuals.
$S$	Variance of fiber distribution.
$\alpha$	Orientation of vertical planes of trusses.
$\bar{\alpha}$	Locator of discrete angle within constant area interval for $f(\theta)$ .
$\beta$	Orientation of fiber pairs in each plane.
$\Delta L/L$	Thermal expansion per unit length per degree Kelvin.
$\theta$	Fiber orientation within continuous fiber distribution.
$\bar{\theta}$	Mean orientation of fiber distribution.
$\sigma$	Stress component.
$\phi$	Fiber orientation within discrete fiber distribution.
$\nu$	Poisson's ratio.
$1, 2, 3$	SPACE cell axes.

## INTRODUCTION

Analytical techniques for predicting the mechanical behavior of rigidized surface insulation materials (RSI) under generalized states of stress were developed by Materials Sciences Corporation (MSC) under contract NAS1-11819 (the results are in Ref. 1). Initial computations indicated that the model was sufficiently realistic to be able to predict the properties of RSI material with reasonable accuracy, given only photomicrographs of the material and some basic fiber material properties. The previous work also demonstrated the ability of the RSI model to predict the sensitivity of various mechanical properties of RSI to changes in the numerous geometric parameters contributing to the final RSI material.

The current effort has been applied to determining how a typical RSI material would behave under combined loading states. In particular, the thermal stress states induced during re-entry of the Space Shuttle were of prime concern. A typical RSI tile was analyzed for re-entry thermal stresses under computed thermal gradients for a model of the RSI material. The results of the thermal stress analyses were then used to aid in defining typical combined stress states for the failure analysis of RSI using the MSC-SPACE Program.

An additional objective of this study was to modify the program described in Ref. 1 to make it more user-oriented. A complete listing of the program and supporting documentation are provided in the Appendices to enable others to utilize the program.

## METHOD OF ANALYSIS

The Reusable Surface Insulation (RSI) Materials studied are rigidized fiber networks. The analysis of RSI materials as developed in Refs. 1 and 2 is based upon the modeling of the actual material by a space frame structure in which each section of fiber between nodes is treated as a beam having some initial curvature. The model utilizes a series of different, regular arrays of trusses, having various orientations, to represent the actual three dimensional fiber array, see Fig. 1. This may be regarded as representing a continuous statistical distribution function by a series of discrete delta functions of differing magnitude (i.e., approximating a curve with a bar graph). The analysis of RSI materials requires treatment of nonhomogeneous materials. When this material is subjected to any loading, the average deformation of the material depends both on the physical and geometrical variabilities of its constituents. The theory of deformation of heterogeneous media, considering physical variability from phase to phase has been reviewed in Ref. 2 and will not be repeated here.

The micromechanical RSI model follows the concept that the three-dimensional random network of fibers can be represented by a basic set of truss elements oriented in different planes, as introduced by Rosen and Bagchi [2]. Results obtained from the analysis of that model have shown encouraging agreement when compared with experimental values. This agreement has motivated the present development of a general model to evaluate the characteristics of RSI material exhibiting both geometrical and material variability. The geometrical and material variabilities of the actual material are represented by a number of trusses oriented in different planes with variable material and geometrical properties. The concept of parallel trusses is introduced to represent such geometric factors as orientation, fiber aspect ratio, eccentricity, volume fraction, etc.

Basically, the approach is to represent the continuous statistical distribution function defining fiber geometry by a series of elements having discrete values of each of the variables. This may be viewed physically as an approximate model, or it may be viewed mathematically as a discrete representation of a continuous function.

Details of the analytical model are available in Refs. 1 and 2. A description of how photomicrograph data of RSI material may be reduced to a useable form, and a description of the input variables required for utilization of the RSI computer program, "SPACE", are provided in the Appendices of this report.

The design and analysis of RSI tiles consist of several major aspects. Design studies require average RSI mechanical properties and a suitable understanding of the failure mechanisms under various loading conditions. Micromechanical analyses can provide average properties based on an understanding of the microstructure of the material and fiber properties. In addition, micromechanical analyses can be utilized to develop a suitable failure criteria to be applied during design studies utilizing average properties and finite element analyses.

Previous studies concentrated upon the mathematical development of the RSI model and subsequent justification of the validity of the model and computer program. During the current study several additional steps have been taken towards utilizing the SPACE program to develop design criteria for RSI materials. A finite element model of an RSI tile was utilized with average RSI properties to determine critical stress states existing in the RSI under a typical set of re-entry heating conditions. Photomicrographs of the RSI were analyzed to generate input for the SPACE Program to develop a micromechanical model of the RSI. The resulting predicted properties of the RSI which were generated from the photomicrograph data and fiber data from Ref. 1, were then compared with experimentally measured properties and excellent agreement was obtained. The RSI model generated by the SPACE Program was then utilized along with the critical stress states as determined by the finite element analyses to develop a set of failure surfaces

for the RSI under combined stresses. The results, as described below, represent the first predictions of the behavior of RSI under combined stress states, based on the micromechanical model.

## RSI TILE ANALYSIS

A typical RSI tile subjected to re-entry heating was analyzed using finite elements and average mechanical properties. The results of the finite element analyses were subsequently used to define both critical stress levels and typical combined stress states existing within the RSI during re-entry heating conditions.

The RSI tile modeled with finite elements is shown in Fig. 2. The model consisted of thirty-one elements along the tile and twenty-four elements through-the-thickness, with symmetry boundary conditions applied along the centerline of the model. An aluminum substrate 3.81 mm thick was assumed, along with a 6.25 mm thick foam pad bonding the RSI material to the aluminum. The properties of the aluminum and foam did not significantly influence the analytical results because only heat-up of the tile was considered and the base of the tile never exceeded 75F.

The average mechanical properties of the RSI and ceramic coating materials, obtained from Ref. 3, are listed in Table 1 as functions of temperature. Through-the-thickness temperature gradients for a typical re-entry heat-up period were also obtained from Ref. 3 and are listed in Table 2.

Several re-entry gradients were analyzed, and it was found that the 240 second gradient yielded the worst stress states in the tile. The highest stresses in the center of the tile were found to be the in-plane stresses several elements under the coating at the centerline, see Fig. 2. The stress state at that location was nearly unidirectional with a magnitude to approximately  $0.1 \text{ MN/m}^2$  in-plane, see Table 3. At the outer edge of the tile (Area 2 of Fig. 2) combined stresses existed with typical magnitudes of  $0.014 \text{ MN/m}^2$ , in the through-the-thickness direction,  $0.07 \text{ MN/m}^2$  in the in-plane direction, and  $0.02 \text{ MN/m}^2$  shear stresses, see also Table 3.

The results of the finite element study of RSI under re-entry heatup conditions indicate that the most useful combined stress failure surface data would be for combined loading conditions of positive tension in both the in-plane and through-the-thickness directions, plus shear stresses. Consequently, the studies with the SPACE Program for combined stress failure were concentrated upon these types of loading conditions.

## ANALYSIS OF RSI UNDER COMBINED STRESSES

Before attempting to predict the behavior of RSI under combined stresses, it was necessary to define a suitable material model for the SPACE Program. An estimate of the fiber properties was available from Ref. 1, and photomicrographs of a typical RSI material were obtained from Ref. 4. In addition, measured mechanical properties of the RSI were available through Ref. 3, thus providing an experimental check on the predicted moduli and strengths in the in-plane and through-the-thickness directions. Assuming that reasonable agreement could be obtained between the predicted and measured properties, one could then place a reasonable degree of confidence in the predicted behavior under combined stress states.

The photomicrographs of RSI were studied to determine fiber distributions in each of the principal planes of the material. The raw photomicrograph data consisted of number of fiber intersections per given line length versus line orientation. The fiber distribution function was assumed to be of the form:

$$\frac{f(\theta)}{\bar{R}} = \frac{1+e \cos 2(\theta - \bar{\theta})}{1 + \frac{2e}{\pi} \sin 2\bar{\theta}} \quad (1)$$

where  $\bar{\theta}$  gives the orientation of the distribution and  $e$  controls the eccentricity, or strength of orientation of the fiber distribution. The method of reducing the photomicrograph data to a fiber distribution function given by equation 1 with  $e$  and  $\bar{\theta}$  known, is given in Appendix A.

Very interesting results were obtained for the fiber distribution functions as obtained from the photomicrograph data. The fiber distributions for the two through-the-thickness sections, the N-S and N-T planes of Fig. 2, were surprisingly similar. The distribution functions for both planes showed  $\bar{\theta} \approx 90^\circ$  and distribution eccentricities of 0.35 and 0.43. In contrast, the third plane photomicrograph, the S-T plane, showed a circular fiber distribution, indicating no preferential fiber orientation.

Figs. 3 through 5 present the photomicrograph data and best fit distribution function, equation 1, to the data for the three planes examined, namely, the N-S, N-T and S-T planes. The data points plotted in Figs. 3 through 5 represent the data obtained from the photomicrographs. That is, each point represents the number of fibers which intersected a given length scanning line which was oriented at an angle of  $\theta + 90^\circ$  at a given location on the photomicrograph. A fixed length scanning line was oriented at  $\theta$  degrees at twenty different locations on each photomicrograph and the number of fibers intersecting the line was determined. The ninety degree shift in the data was required since the highest orientation of fibers would show the largest number of intersections when the scanning line was oriented at  $90^\circ$  to that direction.



Based on the above, an in-plane fiber distribution with an eccentricity of 0.40 and mean fiber angle of  $90^\circ$  was assumed representative of the material in the N-S and N-T planes with no preferential orientation in the S-T plane. Fiber truss angles could thus be defined as in Appendix A. Appendix B provides the data supplied to the SPACE Program to represent the RSI material, and an example of the program input and output are provided in Appendix C.

A comparison of the measured mechanical properties of RSI and those predicted using the SPACE Program and above described model is provided in Table 4. As can be seen, a large variation occurs in the measured properties. Large experimental variations in properties preclude a critical comparison between the analytical model and experimentally determined properties. This does not prove to be a severe shortcoming for the current program, however, because as seen in Table 3, the predicted properties fall well within the range of measured values. The shear modulus is the only property which is out of the range of the experimental data. This difference could arise for several reasons. First, the SPACE Program assumes that the fibers intersect at rigid joints, which would over predict the shear stiffness. Secondly, although test methods do exist, shear properties are difficult to obtain. In the case of RSI, it could be that edge effects may have significantly reduced the effective cross-sectional area of the test specimen, resulting in a substantial reduction in measured shear modulus.

It is significant to note that the model accurately predicts the in-plane and through-the-thickness properties, which are very different in each direction. This result is significant in that the differences between the in-plane and through-the-thickness properties in the SPACE model have a direct correlation to the fiber distributions chosen to represent the spatial distribution of fibers. Consequently, the reasonable agreement between the model and measurement indicates that there is merit in the current method of obtaining fiber distribution data from photomicrographs and reducing the continuous distribution to a discrete distribution.

Given a valid model for the RSI material, various sets of combined stress states were applied to the model to develop an understanding of the behavior of the material under combined stresses. Although the SPACE Program employs incremental loading, the loading increments are applied to all stress components such that the initial stress ratios are maintained. That is, the initial stress tensor is increased in magnitude to failure of the material. Since the finite element analyses indicated that the most severe stress states were combinations of tension through-the-thickness and in-plane, along with shear, the SPACE analyses were concentrated on these cases. Namely, the intersection of the failure surface with the  $\sigma_n - \sigma_s$ ,  $\sigma_n - \sigma_{ns}$ , and  $\sigma_s - \sigma_{ns}$  planes for

room temperature material were determined since these contours would reveal the basic characteristics of the failure surface. Figs. 6 through 8 present the intersections of the failure surface with the above-mentioned planes. Note that the regions of high stresses as defined by the finite element analyses and indicated in Figs. 6 through 8 fall well below the predicted failure surface for re-entry heat-up conditions.

## DISCUSSION

The correlation between the analytical model for RSI and the measured elastic constants and strengths of the RSI in the two principal material directions indicates the validity of the analytical model. In particular, the agreement in elastic moduli in the two principal material directions lends credibility to the method of defining the fiber distributions using photomicrograph data.

The thermal stress analyses of the typical RSI tile provided some critical stress states to be evaluated using the SPACE Program. Since only one re-entry heating cycle was analyzed, one can only assume that the stress states obtained were typical and not necessarily "worst case". However, the intent of the thermal stress analyses was to provide some typical combined stress states, and not as an exercise to determine a "worst case" condition for a typical shuttle mission. The results of the analyses indicated that the most severe combined stresses were tension and shear in the tile.

A large range of combined stresses did not result from the thermal stress analyses. Consequently, those critical stresses were evaluated (in-plane tension and combined tension and shear). In addition, the intersection of the failure surface with the principal stress planes was determined to provide a better indication of the capability of the RSI under combined stresses. These results indicate that a great deal of interaction between stress components occurs for combined stress states, requiring careful consideration of the failure criteria to be used for design purposes.

The overall design of RSI tiles can now incorporate a reasonable failure criteria. That is, the SPACE Program can be utilized to develop a basic RSI model of a current material such that the SPACE Program agrees with experimental data in the principal material planes. One can then perform a series of computations using SPACE to develop an overall failure surface for the RSI, or the program could be utilized as a post analysis program for finite element results. The stress state at each finite element could be used as input to the program and a failure analysis performed for each RSI element. The end result would be a minimum margin of safety or contours of margins of safety.

Many modifications have been made to the SPACE Program, during the study, to make the program user oriented. The primary revisions to the program included changing the formatted input to namelist input, providing multiple case capability within each run, choosing suitable default values for many variables, to simplify choice of input for most RSI analyses, and improved documentation of the output data printed by the program. A description of the input to the program is provided in Appendix B, with a sample case input and output in Appendix C and a complete CDC 6600 listing of the program in Appendix D.

## CONCLUSIONS

The analytical model for RSI material incorporated in the SPACE Program has been shown to be capable of predicting the mechanical properties of RSI material with good accuracy. This achievement is significant because the RSI model is based on the microstructural properties of the RSI as obtained from basic fiber property data and fiber geometry and distribution data obtainable from photomicrographs of the RSI. Thus, given some basic understanding of the material, one can predict mechanical properties, or conversely one can use the SPACE Program to provide some guidelines or goals for the RSI material development.

The combined stress failure study described earlier represents the first attempt to generate a failure criterion for RSI which is based upon the microstructure of the RSI and yet applicable to the design of RSI tiles from a macroscopic, average property, point of view. It is significant to note that no thermal stress cracking of the RSI studied had been observed during testing, and the combined stress study showed that, at least for the re-entry gradients examined, no failures of the RSI would be predicted.

Due to continuing developments in the RSI material, the thermostructural design of RSI tiles should include a model for the failure analysis. The SPACE Program provides such a model which can be used as a post processor to finite element studies, consequently, a complete CDC 6600 listing of the program and its sub-routines is included as an Appendix to this report. Given satisfactory agreement between a SPACE model and one dimensional test data on a given RSI material, one can simply attach that RSI model and the SPACE Program to a post processor for finite element analyses to develop a complete design tool for RSI tiles.

## REFERENCES

1. Rosen, B.W., Bagchi, D.K., and Kibler, J.J., "Analytical Study of Ridigized Fibrous Materials", NASA CR-2371, February 1974.
2. Rosen, B.W. and Bagchi, D.K., "Material Model Studies", NASA CR-112038 (R.A. Tanzilli, Editor).
3. Pigg, O., NASA Johnson Spacecraft Center, Private Communication to L. Vosteen, NASA Langley Center.
4. Chapman, A., NASA Langley, Private Communication.

TABLE 1  
MATERIAL PROPERTIES  
A - RSI MATERIAL

Temp K	$E_N$ MN/m <sup>2</sup>	$E_S = E_T$ MN/m <sup>2</sup>	$G_{NS}$ MN/m <sup>2</sup>	$\nu_{NS} = \nu_{NT} = \nu_{ST}$	$\Delta L/L_N = \Delta L/L_S = \Delta L/L_T$ cm/cm/K
116.	40.0	137.8	24.1	0.10	-2.78E-5
200.	40.0	144.7	25.5		-2.22E-5
297.	41.3	165.4	27.5		0.
478.	46.8	227.4	27.5		0.61E-4
700.	53.7	254.9	27.5		1.56
922.	56.5	268.7	27.5		2.39
1144.	55.8	261.8	27.5		2.89

B - COATING MATERIAL - ISOTROPIC

Temp K	$E_N$ MN/m <sup>2</sup>	$\nu_{NS}$	$\Delta L/L$ cm/cm/K
144.	6.89E4	0.20	-0.67E-4
200.	6.54		-5.00E-5
297.	6.20		0.
478.	6.20		1.06E-4
700.	6.20		2.28E-4
922.	4.82		3.39E-4
1144.	3.44E4		4.06E-4
1422.	6.89E2		-2.22E-5
1533.	6.89E1		-2.22E-5

TABLE 2  
TEMPERATURE DISTRIBUTION THROUGH RSI FOR VARIOUS  
RE-ENTRY HEATING TIMES

Distance From Outer Surface  mm	Temperature, K, at Time				
	120sec	160sec	200sec	240sec	300sec
0.00	711	810	939	1102	1340
2.50	624	696	804	941	1182
4.75	521	560	621	711	901
8.50	416	433	456	489	569
14.12	346	355	365	378	404
21.62	315	320	325	331	342
29.12	300	301	302	304	306
40.37	297	298	298	298	298
55.37		297	297	297	298
66.62	↓	↓	↓	↓	297
74.12					↓
∞	297	297	297	297	297

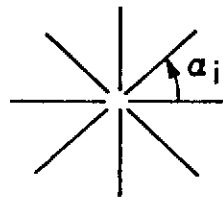
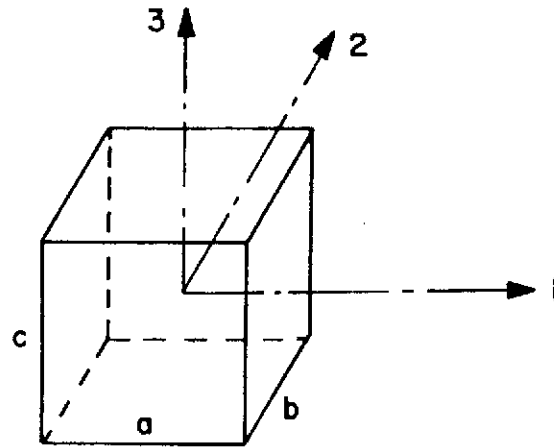
TABLE 3  
SUMMARY OF MAXIMUM STRESSES FOR  
RE-ENTRY HEATING GRADIENTS IN TABLE 2

Area of Stresses See Figure 2	In-Plane Stress <u>MN/m<sup>2</sup></u>	Through Thickness Stress <u>MN/m<sup>2</sup></u>	Shear Stress <u>MN/m<sup>2</sup></u>
Area 1 Center of Tile	0.10	0.	0.
Area 2 Edge of Tile	0.07	0.014	0.02

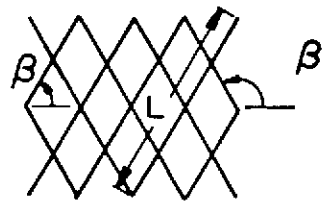
TABLE 4  
MEASURED AND PREDICTED PROPERTIES OF RSI  
AT ROOM TEMPERATURE

<u>Property</u>	<u>Measured Value</u> (MN/m <sup>2</sup> )		<u>Predicted by</u> <u>SPACE (MN/m<sup>2</sup>)</u>
	<u>Mean</u>	<u>Range</u>	
In-Plane Modulus = $E_S = E_T$	227	124+275	144.
Through Thickness Modulus = $E_N$	46.8	26+60.6	48.2
Shear Modulus = $G_{NS}$	27.5	6.9+34.4	82.7
In-Plane Tensile Strength	.200	*	.205
Through Thickness Tensile Strength	.055	*	.069
Shear Strength	.103	*	.117

\*Design Allowable Value

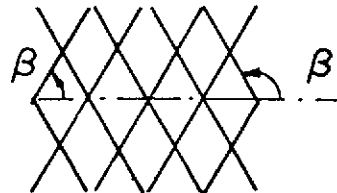


LAYOUT OF VERTICAL TRUSSES



TYPICAL VERTICAL TRUSS

$n$  = NUMBER OF "BAYS"  
= NUMBER OF SEGMENTS  
PER FIBER



$L$  = FIBER LENGTH

LAYOUT OF HORIZONTAL TRUSS

Figure 1. - A typical space model.



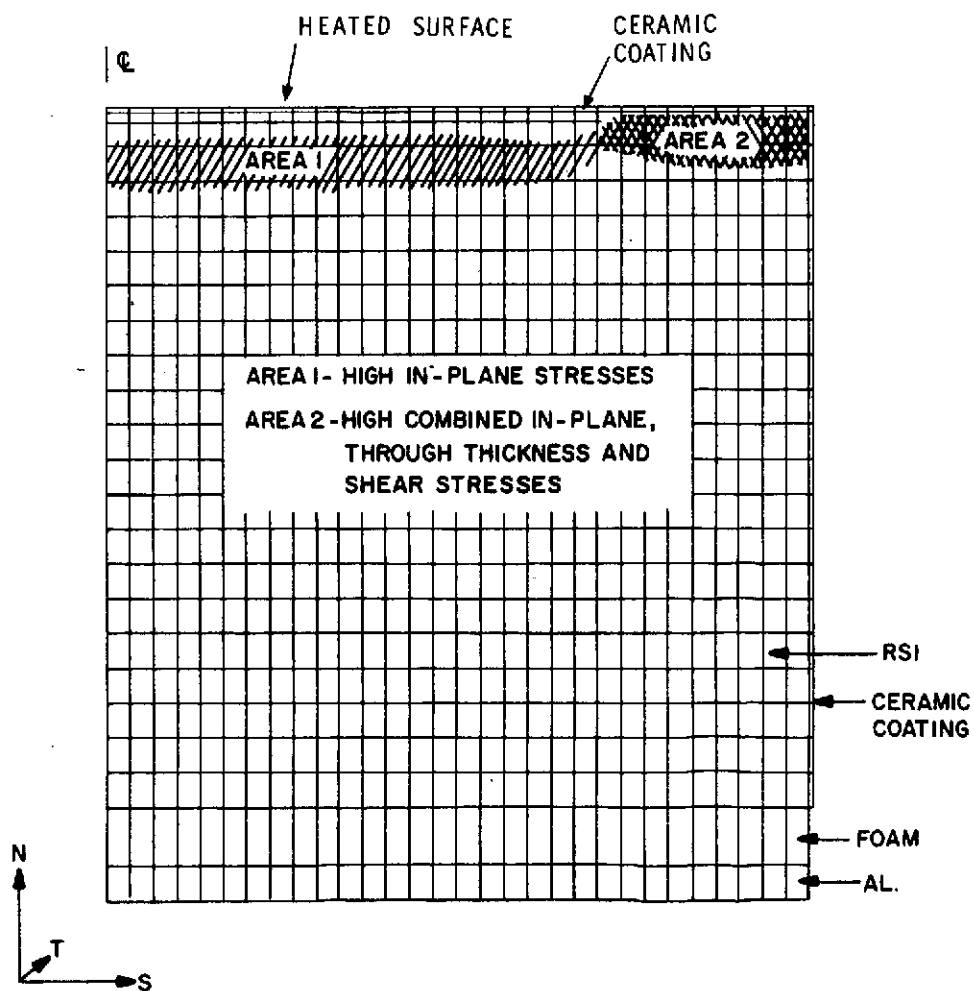
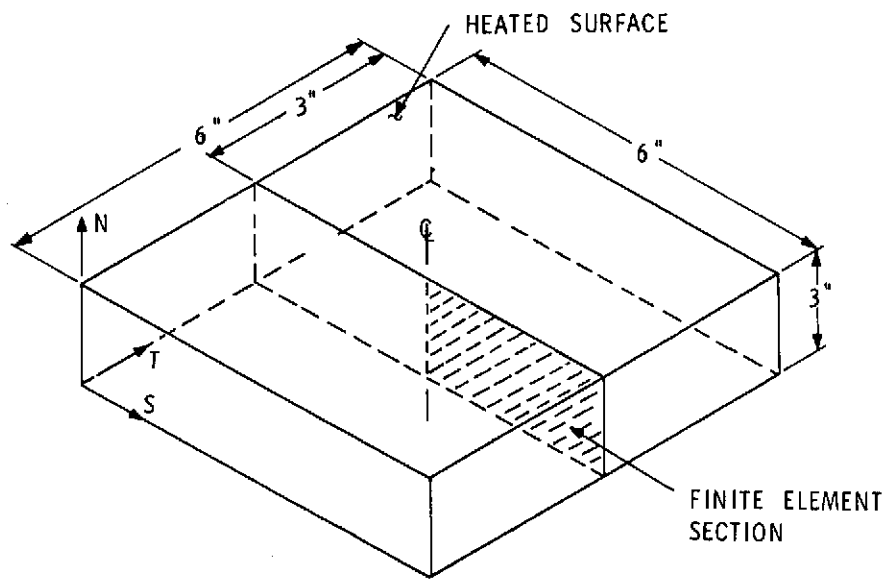


FIGURE 2 - FINITE ELEMENT MODEL OF RSI TILE.

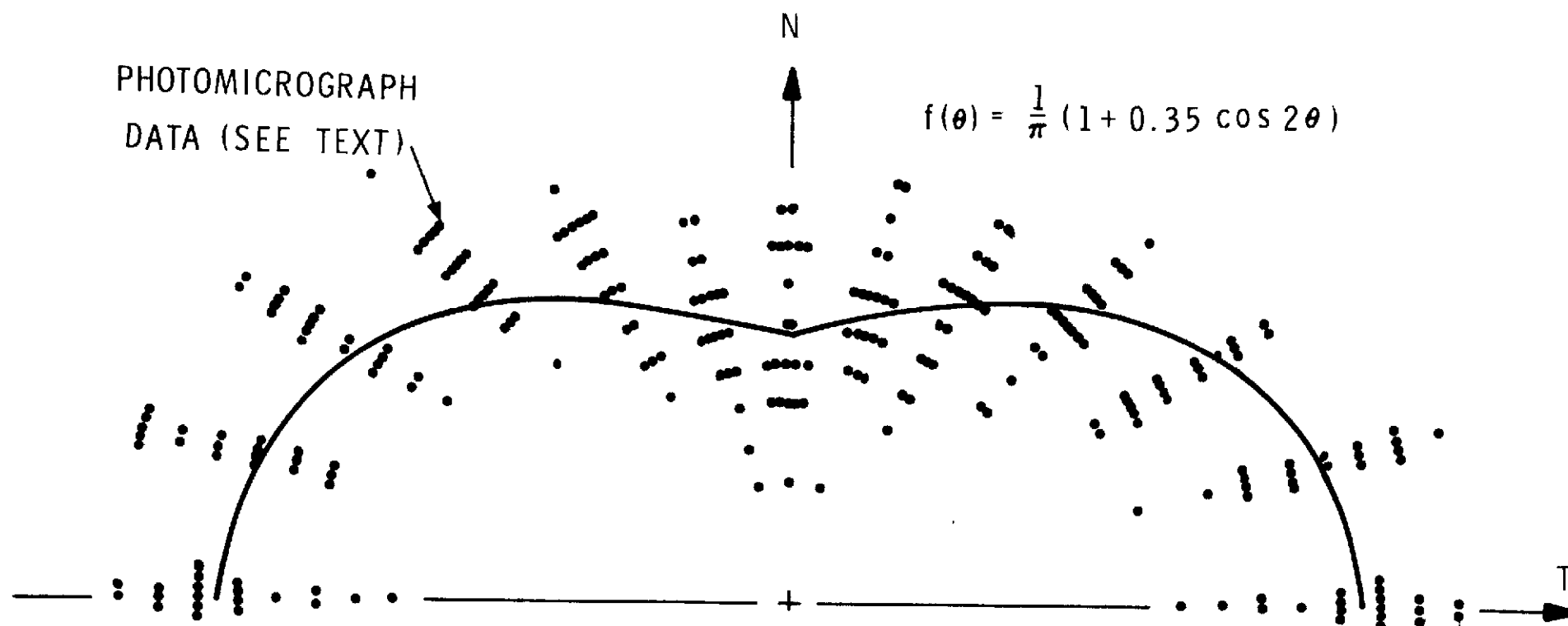


Figure 3. - RSI Fiber Distribution in the N-T plane of the tile.

$$e = 0.35$$

$$\bar{\theta} = 90^\circ$$

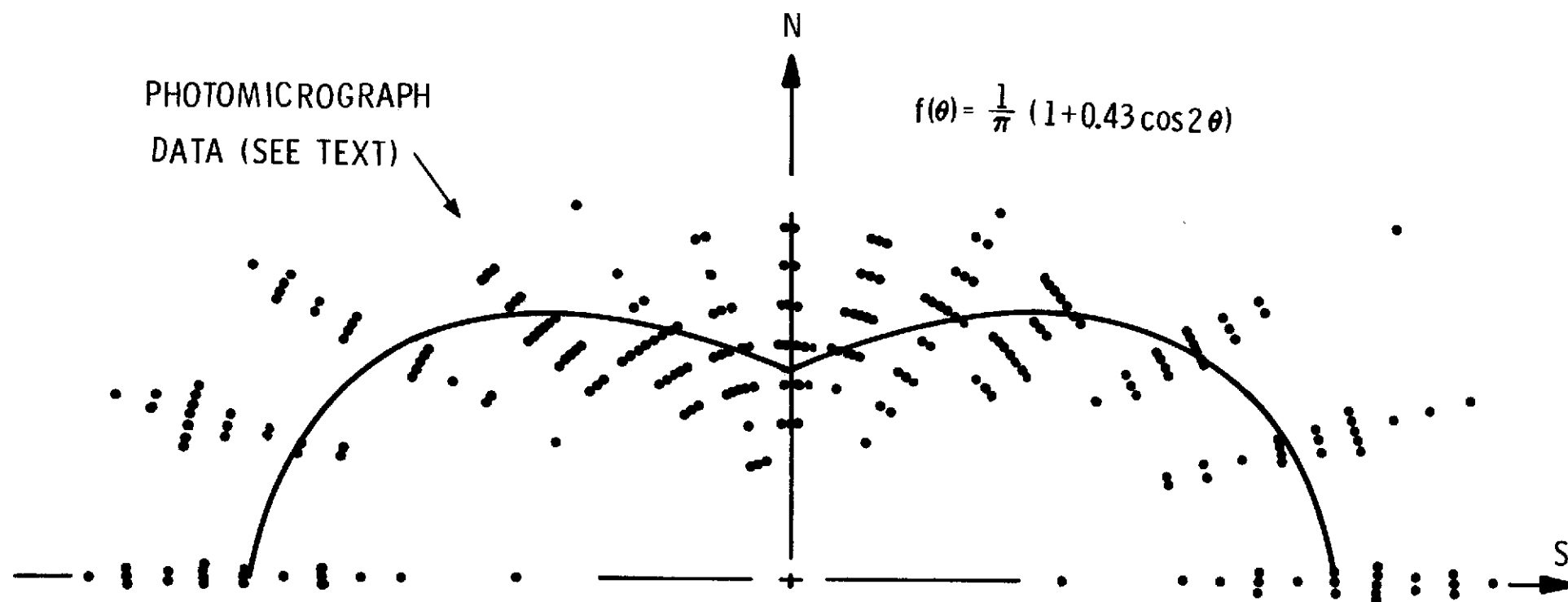


Figure 4. - RSI Fiber Distribution in N-S plane of the tile.

$$e = 0.43$$

$$\bar{\theta} = 90^\circ$$

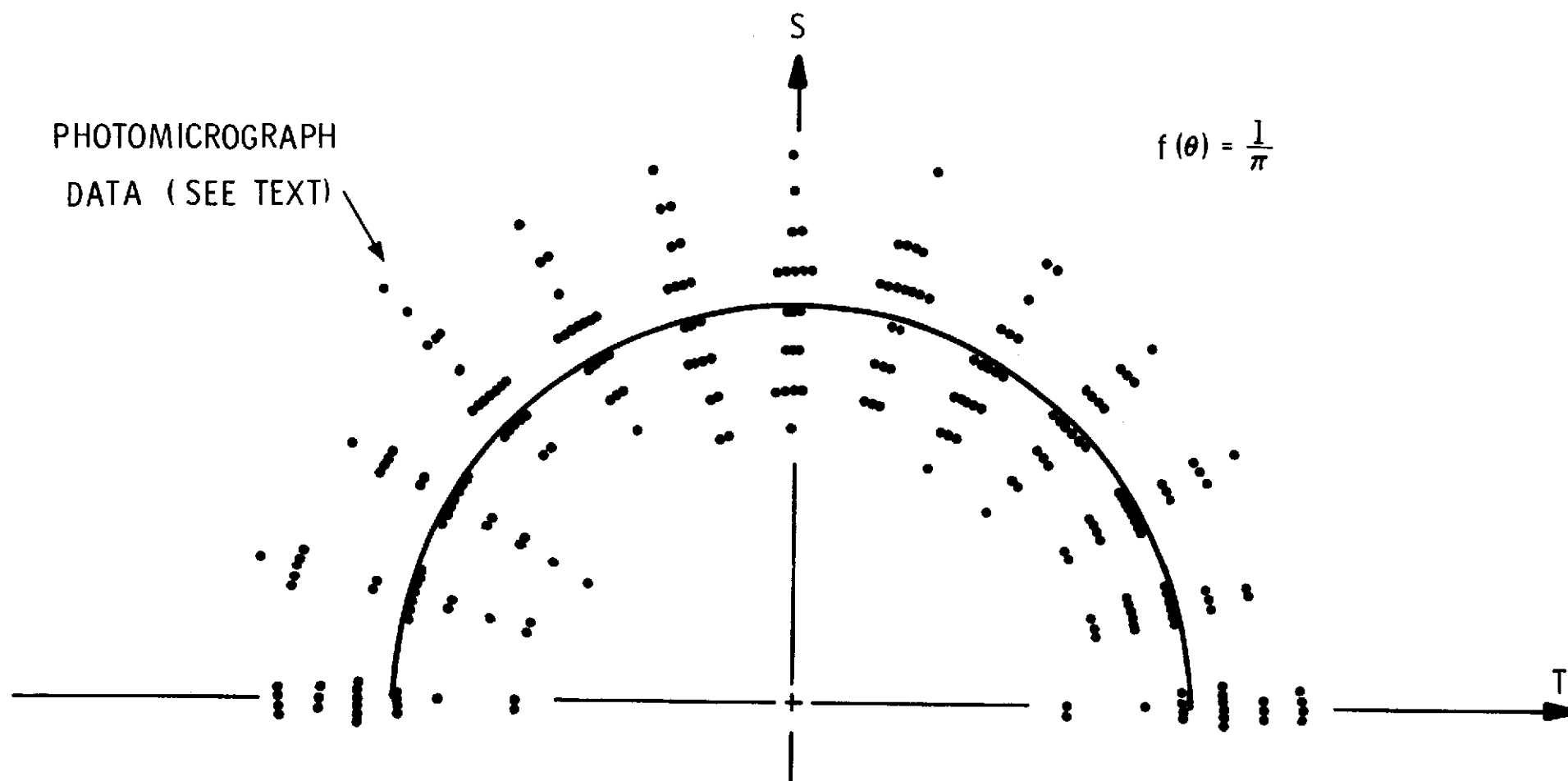


Figure 5. - RSI Fiber Distribution in the S-T plane.

$$e = 0.0$$

$\bar{\theta}$  = undefined - i.e., distribution circular

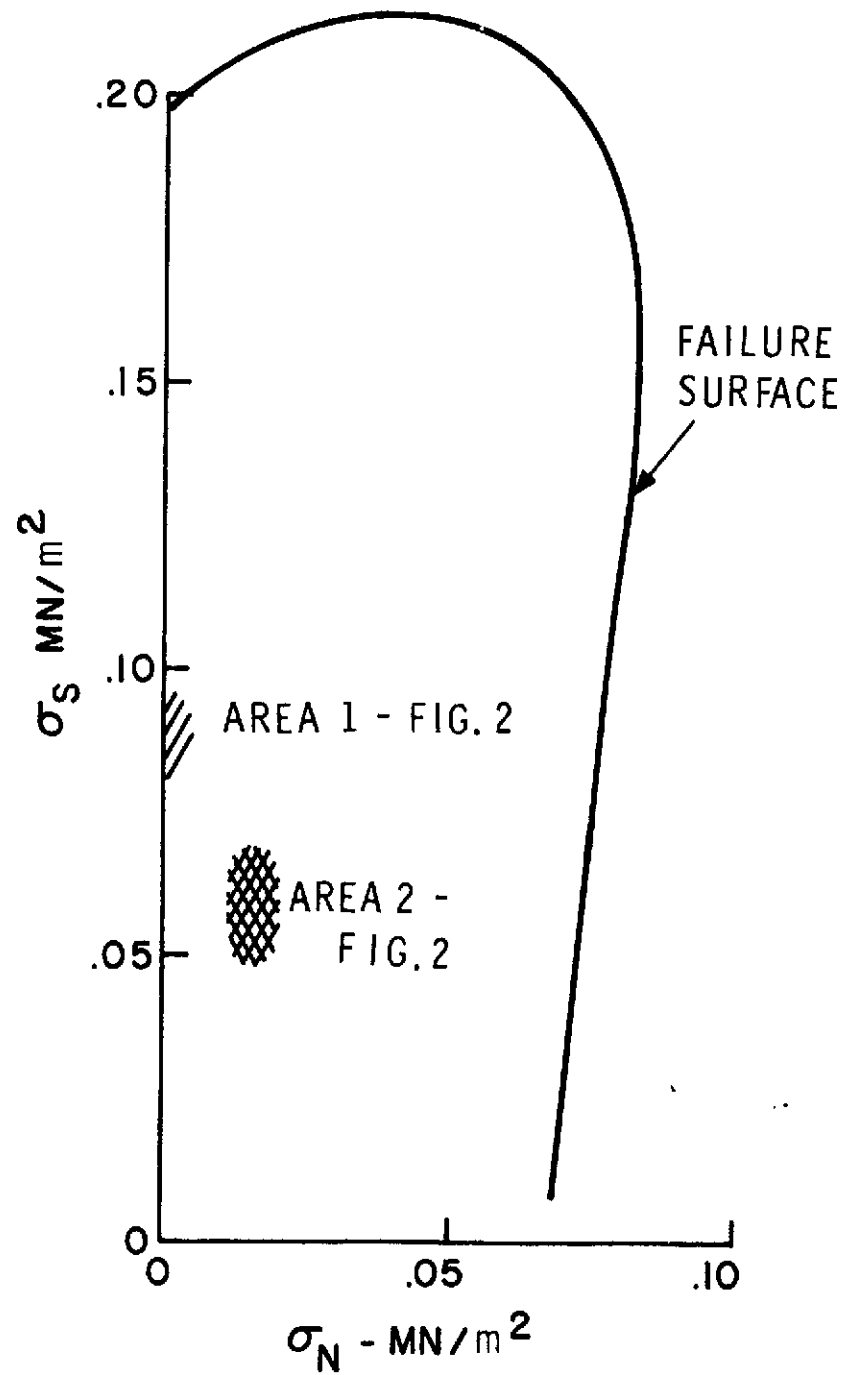


Figure 6. - Failure surface in  $\sigma_N - \sigma_S$  plane.

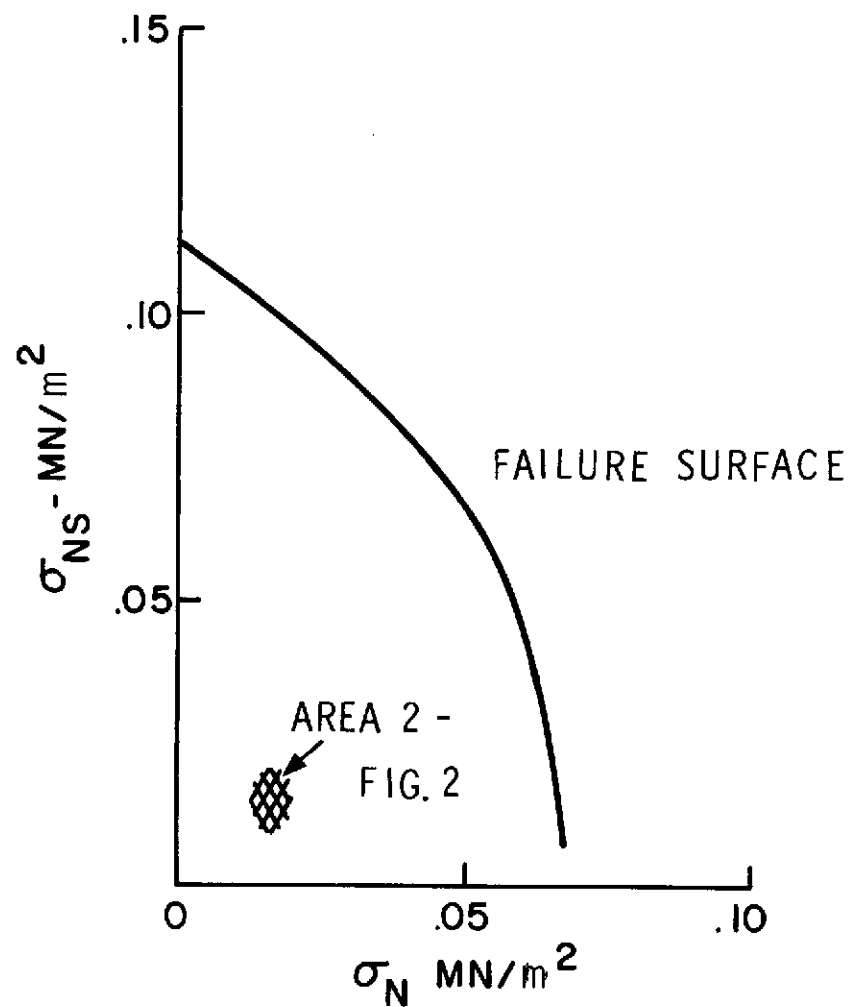


Figure 7. - Failure surface in  $\sigma_N$  -  $\sigma_{NS}$  plane.

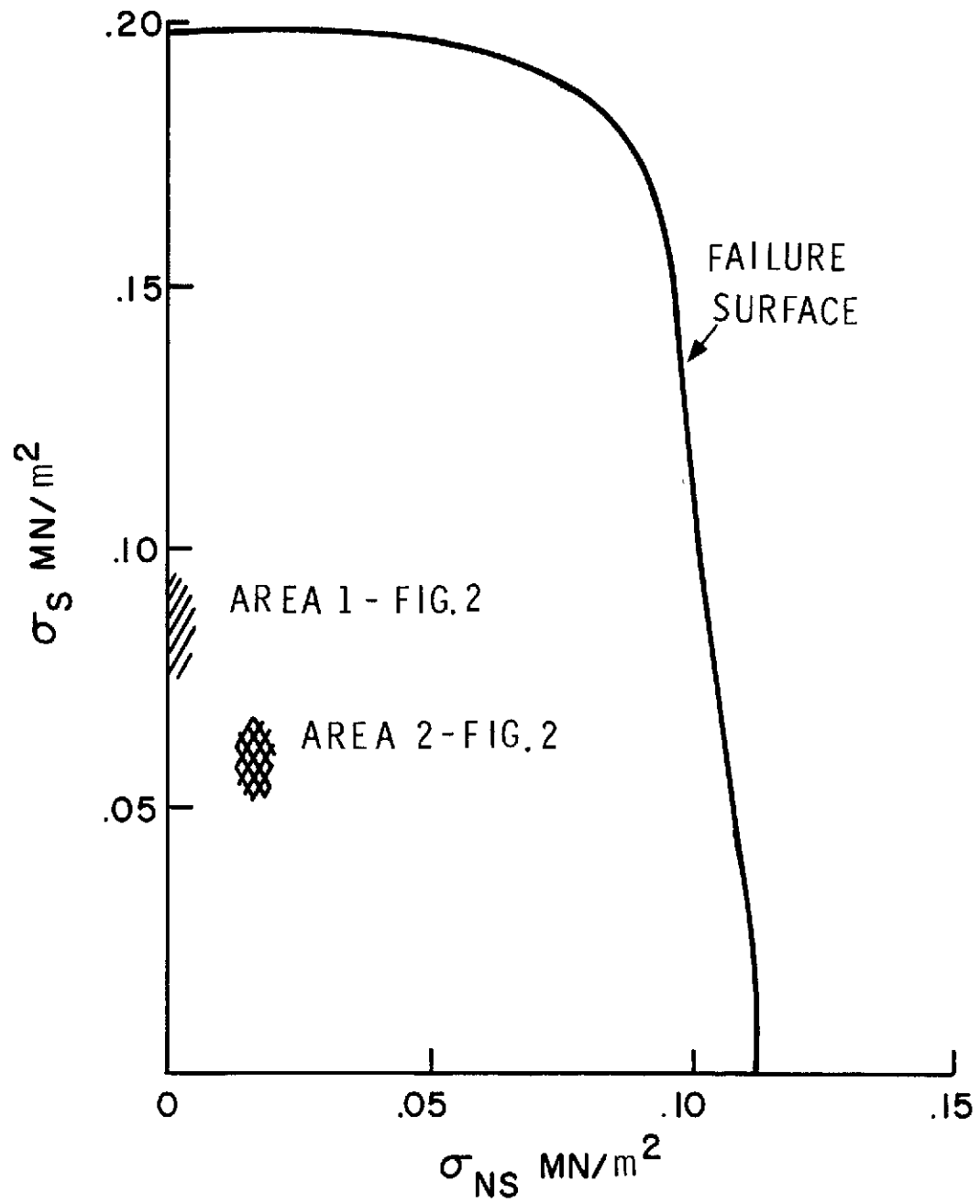


Figure 8. - Failure surface in  $\sigma_S - \sigma_{NS}$  plane.

## APPENDIX A - REDUCTION OF PHOTOMICROGRAPH DATA

### A.1 Discrete Representation of a Continuous Distribution Function:

The space frame analysis program requires representing continuous distribution functions with a discrete number of points. Spatial orientation of fibers, fiber diameters, length between fiber intersections, fiber eccentricities and fiber strengths all possess continuous distribution functions. Analytical representation of RSI material requires identifying a deterministic set of fiber properties which can be modeled with a finite number of trusses with fixed properties. The following section describes how a continuous distribution can be represented by a discrete distribution of finite number of samples. In particular, the spatial distribution of fibers in any given plane is considered. However, once the continuous distribution function for any of the variables is defined, the discrete representation of the variable can be determined in analogous fashion.

It is first assumed that the continuous distribution function of a variable is known, in this case the angular orientation of RSI fiber in a given plane. It has been assumed that the distribution can be represented as a first approximation by an elliptical distribution  $f(\theta)$  such that

$$f(\theta) = \frac{1}{\pi} (1 + e \cos 2\theta) \quad (A-1)$$

where  $e$  is a measure of the eccentricity of the ellipse and  $\theta$  is understood to be the angle of a fiber as measured from the mean angle or preferred fiber orientation. In practice the mean angle,  $\bar{\theta}$ , and eccentricity can be determined by using scanning lines, on photomicrographs of RSI material. Namely, the number of fiber intersections with the scanning line, versus orientation of the scanning line will provide an experimental distribution of  $f(\theta)$ . A large number of scanning lines located at various areas of RSI material are employed to give a good representation of  $f(\theta)$ , the mean value of  $\theta$  can be found and the eccentricity can be determined in a least squares sense, the results of which are described in the following section.

The discrete representation of  $f(\theta)$  is given by

$$g(\phi) = \sum_{-N/2}^{N/2} \frac{1}{N} \phi_i \quad (A-2)$$

where  $N$  is the total number of points and  $\phi_{-i} = \phi_i$  implying that  $\phi_i$  is normalized with respect to the mean such that the mean values of  $f(\theta)$  and  $g(\phi)$  are zero. Specific values of  $\phi_i$  are determined as follows:



$f(\theta)$  is divided into  $N$  regions such that

$$\int_{\theta_{n-1}}^{\theta_n} f(\theta) d\theta = \frac{1}{N} ; \quad n = 1, \dots, N \quad (A-3)$$

and one value of  $\phi_i$  is located within each resulting interval. Each  $\phi_i$  could be placed anywhere within the interval  $\theta_{n-1}$  to  $\theta_n$ , and the general solution requires satisfying the first  $N+1$  moments of  $f(\theta)$  in order to determine each  $\phi_i$  location. However, a reasonable approximation of  $f(\theta)$  can be made by placing all values of  $\phi_i$  in the same relative position within  $\theta_{n-1}$  and  $\theta_n$  and minimizing the difference between the second moments of  $f(\theta)$  and  $g(\phi)$ . One thus obtains the following expression to be solved for  $\bar{\alpha}$ , the position of the discrete variable  $\phi_i$  between  $\theta_{n-1}$  and  $\theta_n$

$$\sum_{n=1}^{N/2} \frac{2}{N} \{ \theta_{n-1} + \bar{\alpha} (\theta_n - \theta_{n-1}) \}^2 - S = 0 \quad (A-4)$$

where  $S = \frac{1}{2} \left( \frac{\pi^2}{6} - e \right)$  is the variance of  $f(\theta)$

$\theta_{n-1} \rightarrow \theta_n$  defines the equal area intervals of  $f(\theta)$

$N$  is the number of fibers =  $\frac{1}{2}$  the number of discrete trusses (each truss has  $\pm\theta$  fibers)

An example is tabulated in Table A-1 giving the desired positions of  $\phi_i$  for various values of  $N$ . A graphical representation of two continuous distributions for  $e=0.3$  and  $0.95$  along with the discrete representations of the distributions are given in Figures A-1 and A-2.

The above approach is valid for a standard elliptical distribution. However, when one considers how a preferred mean value of fiber orientation may occur during manufacture, a slight modification to the elliptical distribution appears appropriate. Assuming that the manufacturing process starts with a slurry of completely randomly oriented fibers, and then pressure is applied to compress the slurry, it is reasonable to assume that the fiber distribution will be symmetric about both the in-plane and through-the-thickness directions. This can be accomplished by defining  $f(\theta)$  such that

$$f(\theta) = \text{const.} (1 + e \cos 2(\theta - j\bar{\theta})) \quad (A-5)$$

where

$$j = 1 \quad \text{if} \quad 0 \leq \theta \leq \pi/2$$

$$\pi < \theta \leq 3\pi/2$$

$$j = -1 \quad \text{if} \quad \pi/2 < \theta \leq \pi$$

$$3\pi/2 < \theta < 2\pi$$

and results in the distribution shown in Figure A-3. The function,  $f(\theta)$ , is normalized such that the mean value of  $f(\theta)$  between 0 and  $\pi/2$  is equal to the mean of the data,  $\bar{R}$ , i.e.

$$\int_0^{\pi/2} (\bar{R} - f(\theta)) d\theta = 0 \quad (\text{A-6})$$

which results in

$$\frac{f(\theta)}{\bar{R}} = \frac{1 + e \cos 2(\theta - j\bar{\theta})}{1 + \frac{2e}{\pi} \sin 2\bar{\theta}} \quad (\text{A-7})$$

Note that, when normalized, the constant for  $f(\theta)$  becomes a function of the orientation and eccentricity of the distribution. Although the process is slightly more involved algebraically, equal area intervals and discrete locations for placement of discrete points can be determined in the same manner as previously outlined. Substituting equation A-7 into equation A-3 one obtains

$$\theta_i + \frac{e}{2} \sin 2(\theta_i - \bar{\theta}) =$$

$$\frac{i}{N} (1 + 2 \frac{e}{\pi} \sin 2\bar{\theta}) - \frac{e}{2} \sin 2\bar{\theta} \quad (\text{A-8})$$

where  $i = 1, 2, \dots, N/2$

from which one can obtain  $\theta_i$  and define the equal area intervals. For most applications one can locate  $\phi_i$  midway between  $\theta_i$  and  $\theta_{i+1}$ . For a more accurate representation one can solve for  $\bar{\theta}$  in equation A-4, substituting the variance of equation A-7 for  $S$  in equation A-4. In addition, data points taken from RSI photomicrographs can be fit to equation A-7 in the least squares sense to define  $\bar{\theta}$  and  $e$ ; the solution involving solution of a pair of non-linear equations to determine  $\bar{\theta}$  and  $e$ , as described below.

## A.2 Least Squares Curve Fit to Distribution Functions

Given data from the photomicrographs of RSI material which can be tabulated as number of fiber intersections,  $f_i$ , with scanning line versus angular orientation,  $\theta_i$ , of scanning line, one can determine the best fit values of  $e$  and  $\bar{\theta}$  in the following manner.

Define the sum of the squared residuals for equation A-7 as

$$V = \sum_{i=1}^N \left\{ f_i - \frac{1 + e \cos 2(\theta_i - \bar{\theta})}{1 + \frac{2e}{\pi} \sin 2\bar{\theta}} \right\}^2 \quad (A-9)$$

Note that here  $f_i$  represents the data points divided by the mean value of the data measurements.

Since it is desired to minimize  $V$  by proper selection of  $e$  and  $\theta$ , we require

$$\frac{\partial V}{\partial e} = 0 \quad (A-10)$$

$$\frac{\partial V}{\partial \bar{\theta}} = 0$$

Taking the partial derivatives, and after some manipulation, one can solve each equation explicitly for  $e$  in terms of  $\bar{\theta}$  as shown below:

From  $\frac{\partial V}{\partial e} = 0$  one obtains

$$e = \frac{A_2 \cos 2\bar{\theta} + A_1 \sin 2\bar{\theta}}{A_3 \sin^2 2\bar{\theta} + A_4 \cos^2 2\bar{\theta} + A_5 \sin 2\bar{\theta} \cos 2\bar{\theta}} \quad (A-11)$$

where

$$A_1 = \frac{\pi}{2} \sum (f_i - 1) \sin 2\theta_i$$

$$A_2 = \frac{\pi}{2} \sum (f_i - 1) \cos 2\theta_i$$

$$A_3 = \frac{\pi}{2} \sum \sin^2 2\theta_i + \frac{2}{\pi} \sum f_i - \sum (f_i + 1) \sin 2\theta_i$$

$$A_4 = \frac{\pi}{2} \sum \cos^2 2\theta_i$$

$$A_5 = \pi \sum \sin 2\theta_i \cos 2\theta_i - \sum (f_i + 1) \cos 2\theta_i$$

and where  $\sum$  represents summation over the number of experimental data pairs,  $N$ . Note also that the  $f_i$  values are divided by the mean value of  $f_i$  as required to maintain a normalized distribution function.

From  $\frac{\partial V}{\partial \bar{\theta}} = 0$  one obtain

$$e = \{ -B \pm \sqrt{B^2 - 4AC} \} / (2A) \quad (A-12)$$

where

$$A = a_1 \sin 2\bar{\theta} + a_2 \cos 2\bar{\theta}$$

$$B = b_1 \sin 2\bar{\theta} \cos 2\bar{\theta} + b_2 \sin^2 2\bar{\theta} + b_3 \cos^2 2\bar{\theta} \\ + b_4 \cos 4\bar{\theta} + b_5 \sin 4\bar{\theta} + b_6$$

$$C = c_1 \cos 2\bar{\theta} + c_2 \sin 2\bar{\theta}$$

and where

$$a_1 = \frac{2}{\pi} \sum f_i \cos 2\theta_i - \sum \sin 2\theta_i \cos 2\theta_i$$

$$a_2 = - \sum \cos^2 2\theta_i$$

$$b_1 = \frac{2}{\pi} \sum f_i - \sum (f_i + 1) \sin 2\theta_i$$

$$b_2 = \sum f_i \cos 2\theta_i$$

$$b_3 = - \sum \cos 2\theta_i$$

$$b_4 = \frac{\pi}{4} \sum \sin 4\theta_i$$

$$b_5 = - \frac{\pi}{4} \sum \cos 4\theta_i$$

$$b_6 = \sum (f_i - 1) \cos 2\theta_i$$

$$c_1 = \sum (f_i - 1) - \frac{\pi}{2} \sum (f_i - 1) \sin 2\theta_i$$

$$c_2 = \frac{\pi}{2} \sum (f_i - 1) \cos 2\theta_i$$

Solution for  $e$  and  $\bar{\theta}$  can be obtained from equations A-11 and A-12 by simply substituting various values of  $\bar{\theta}$  and plotting the resultant values of  $e$  until an intersection of the two curves is obtained, noting the restrictions that the derivation requires  $e \leq 1.0$ , and  $0 \leq \bar{\theta} \leq \pi/2$ .

TABLE A-1

Values of  $\phi_i$  for Representation of  $f(\theta)$   
 Given by Equation A-1 at  $e = 0.95$

$\phi_i \backslash N$	2	4	6	8	10	12	16	20
1	33.96	8.52	5.54	4.19	3.40	2.88	2.22	1.93
2		47.26	22.44	16.32	12.94	10.75	8.08	6.60
3			54.08	30.37	23.30	19.07	14.10	11.36
4				58.36	35.72	28.34	20.47	16.28
5					61.38	39.70	27.41	21.45
6						63.65	35.35	27.01
7							45.34	33.18
8							66.93	40.35
9								49.56
10								70.11
$\alpha =$	.3773	.3467	.3502	.3569	.3639	.3703	.3819	.4156

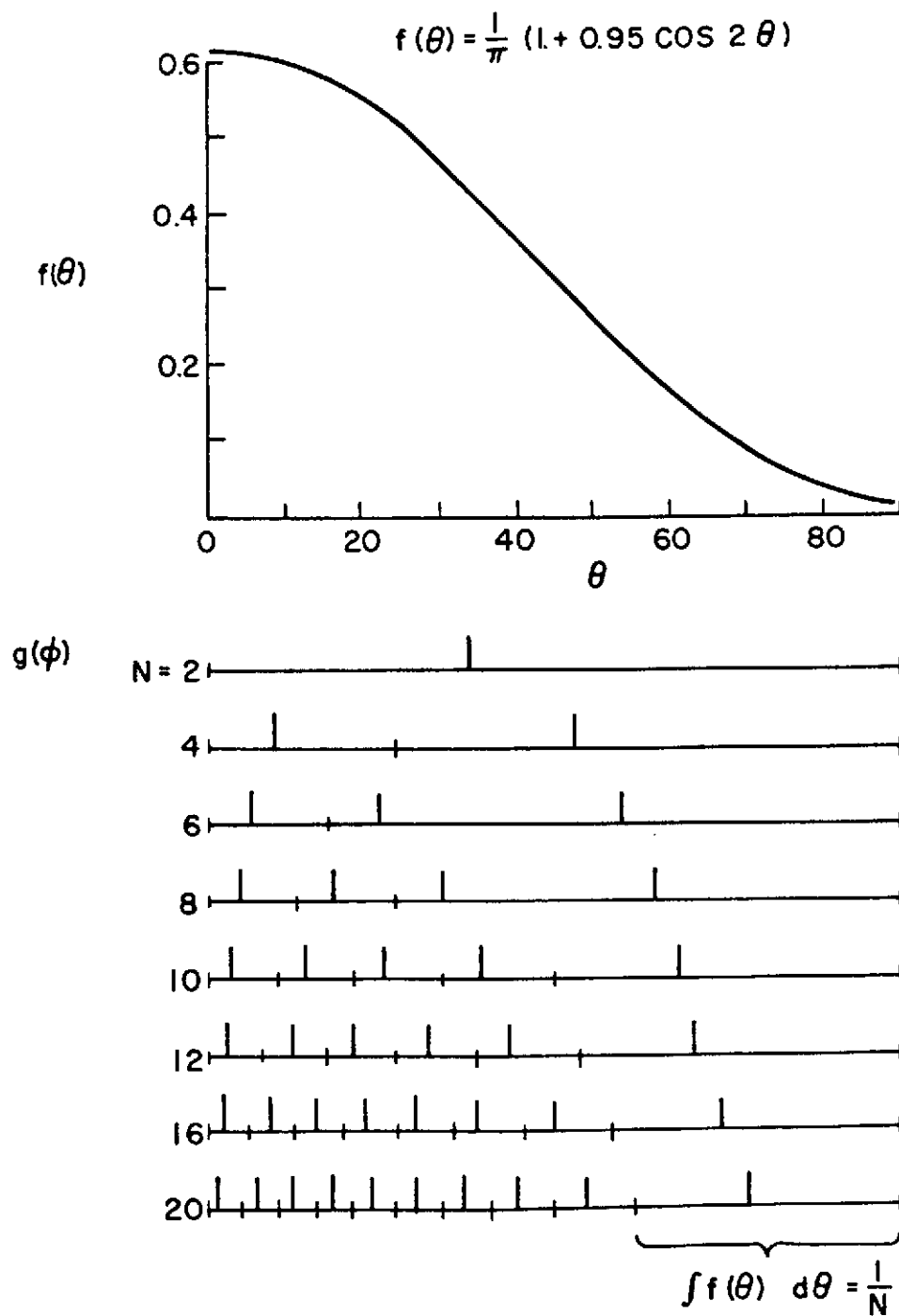


Figure A-1 - Continuous and Discrete Distributions.

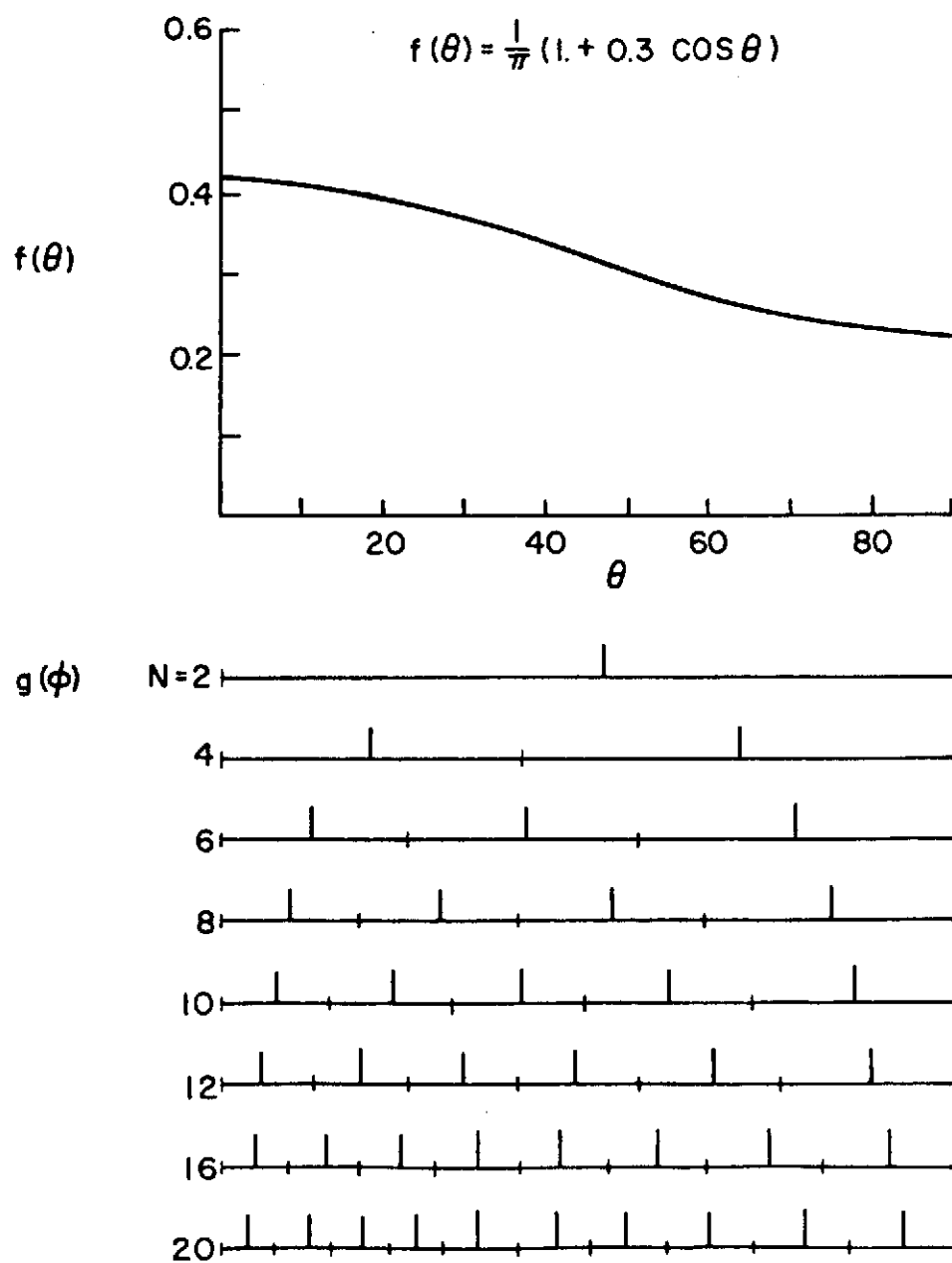
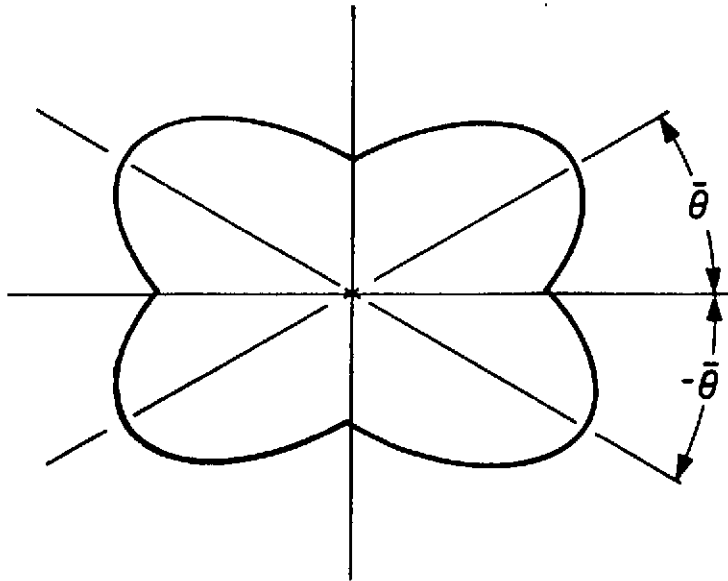


Figure A-2 - Continuous and Discrete Distributions.



$$f(\theta) = \frac{1 + e \cos 2(\theta = j \bar{\theta})}{1 + \frac{2e}{\pi} \sin 2 \bar{\theta}}$$

$$j = +1 \text{ if } 0 \leq \theta \leq \pi/2$$

$$\pi < \theta \leq 3\pi/2$$

$$j = -1 \text{ if } \pi/2 < \theta \leq \pi$$

$$3\frac{\pi}{2} < \theta < 2\pi$$

Figure A-3 - Fiber Distribution for RSI Material.



## SPACE FRAME ANALYSIS PROGRAM

### APPENDIX B

#### B-1 Program Description

The SPACE Program is a space frame analysis program developed by Materials Sciences Corporation (MSC) for the analysis of three dimensional fibrous materials such as RSI. The various materials being developed for reusable space shuttle insulation have several common factors. The materials are all very low density fibrous systems, which, on a microscale, appear as three-dimensional arrays of trusses with small amounts of matrix material located at the fiber intersections. This observation lead to the development of a micromechanical model of RSI, Ref. 1,2, which can be used to assess the effects of various processing and geometric parameters on the structural properties of RSI.

The SPACE Program treats planar arrays of fiber trusses, wherein the planar arrays are oriented at user specified angles in space. Fiber mechanical and strength properties are supplied by the user for each truss in the model, thereby allowing for inclusion of the effects of variable material properties in the fibers. Additional input data controls the geometric parameters, namely fiber length to diameter ratio between fiber intersections, initial fiber curvatures, fiber orientations within each plane, and orientations of the planes in space. Finally, the applied loading, in three-dimensional stress space, is input to the program.

Given the above data, the program computes the stress/strain response of the defined material under the given loading. Incremental loading is applied since the initial fiber curvature introduces non-linearity in that the effective fiber stiffness is a function of the applied load.

The program prints the strain state for each load increment such that the nonlinear stress/strain behavior can be observed. In addition, each fiber pair (truss) is checked at each load increment to determine if its ultimate stress has been exceeded. If a truss breaks, it is eliminated from the model, and the model stiffness and redistributed fiber stresses are recomputed at the breaking load. If further trusses break, they are eliminated also, until either the complete model collapses, or a stable configuration is obtained. If a stable configuration is obtained, the loading is then increased until an additional truss fails, at which time the same process as above is repeated until complete failure of the model is attained. Details of the analytical treatment in the program have been described in Refs. 1 and 2 and will not be repeated here. A flow diagram describing the major paths of information flow and calculations are given in Figure B-1. The remainder of Appendix B describes the input requirements of the

program. Appendix C gives a sample case describing the program output, while Appendix D provides a list of the program applicable to a CDC 6600 computer, utilizing the RUN compiler.

Effective utilization of the SPACE Program requires determining the constituent material geometry and properties of the fibers forming the RSI material. That is, the fiber properties must be known, along with the variability of the fibers in the material. An effective approach to determining the spatial distribution of fibers and representing that distribution with a relatively small number of trusses has been described in detail in Appendix A.

All input to the program is accomplished through a namelist ("DATA") format for ease of keeping track of the values given to each variable for a given deck setup. The input can be broken into three main areas: control parameters determine the number of iterations permitted per stress solution, and define the convergence and divergence criteria for the iterative solution scheme. Geometry definition variables comprise the major input values and provide a complete description of the material model and fiber properties. Finally, the applied loading variables define the initial stress state to be applied to the model, the number of stress increments to be permitted and the size of each stress increment. Many of the variables have default values defined in the program to minimize the input required. A listing of the input variables along with their physical description and default values follows.

It should be pointed out that the program is written such that multiple cases can be executed during one computer run by simply adding additional namelist sets with the data to be changed for each case. That is, the program executes the current case and searches the input data for an additional input namelist, if none exists, the program terminates. The only restriction to the above method of running multiple cases is that the angular orientation of the fibers in each truss must not be changed. That is, BT (I,J) may only be input in the first namelist, all other variables may be changed in successive runs.

## B-2 Program Input Variables

### Control Parameters

NIT	Number of iterations permitted for determining strains and stresses for a particular value of constant applied stress. (Default value is 5)
SEPS	Convergence parameter for iterations, i.e., if two successive stress states differ by less than this value, solution has converged. (Default value is 0.5)

SUPB Divergence parameter for iterations, i.e., if two successive stress states differ by this value, solution has diverged and execution on that load case terminates. (Default value is 1.E+5)

#### Geometry Definition Variables

NOR Number of vertical planes of trusses. These are perpendicular to one plane of fibers. Maximum value is four.

NTR Number of fiber orientations per plane. Each plane is assumed to have the same number of fiber pairs. Maximum value is thirty.

AD,BD,DD Dimensions of the unit cell of material being considered. (Default values AD=BD=DD=1.0)

SGM(I,J) Allowable fiber strength for each fiber in the  $J^{\text{th}}$  truss of the  $I^{\text{th}}$  plane.  
 $J = 1 \rightarrow \text{NTR}$   
 $I = 1 \rightarrow \text{NOR} + 1$   
 The  $(\text{NOR} + 1)^{\text{th}}$  plane is the horizontal plane, See Fig. 1. Note that the 1,2 and 3 directions in the SPACE Program are unrelated to the RSI coordinates, allowing the user to let the single plane of fibers, i.e., the 2-3 plane, to represent whatever RSI orientation appears suitable. In the sample case, Appendix C, the major material distribution differences are in the N-S and N-T planes, consequently the model was defined so that the 1-direction was parallel to the N direction of the RSI, with the 2- and 3-directions being parallel to the S- and T-directions respectively.

RAT(I,J) Fiber length to diameter ratio between joints.

EC(I,J) Eccentricity of fibers (initial midspan deflection in fiber diameters).

EY(I,J) Youngs modulus of fibers.

L(I,J) Length of each truss (cannot exceed unit cell dimensions).

VTI(I,J) Volume fraction of each truss in the model.

TEMP(J),J=1,3 Linear temperature variation in 1,2, 3 directions across material element.

ALPHA Fiber coefficient of expansion, constant for all fibers.

NB(I,J) Number of bays, or intersections, per fiber.

BT(I,J) Angular orientation of fibers in the  $J^{\text{th}}$  truss of  $I^{\text{th}}$  plane, degrees.

AL(I) Angular orientation of  $I^{\text{th}}$  plane  $I=1 \rightarrow \text{NOR}$ .

### Applied Loading Variables

SGO(I,1)	I=1,6 Applied initial stress state on model I=1; $\sigma_{11}$ I=4; $\sigma_{23}$ I=2; $\sigma_{22}$ I=5; $\sigma_{13}$ I=3; $\sigma_{33}$ I=6; $\sigma_{12}$
NINC	Maximum number of loading increments. (Default value is 100)
MSCAL	Maximum number of re-evaluations of stress distributions per loading. (Used to curtail calculations if model cannot sustain loading at a given load level) (Default value is 5)
SMLT	Stress increment multiple. Stresses increment in steps of (initial stress) * SMLT (Default value is 1.0) Note that SMLT increases the magnitude of the stress tensor and not the direction.

SPACE FRAME ANALYSIS PROGRAM FLOW

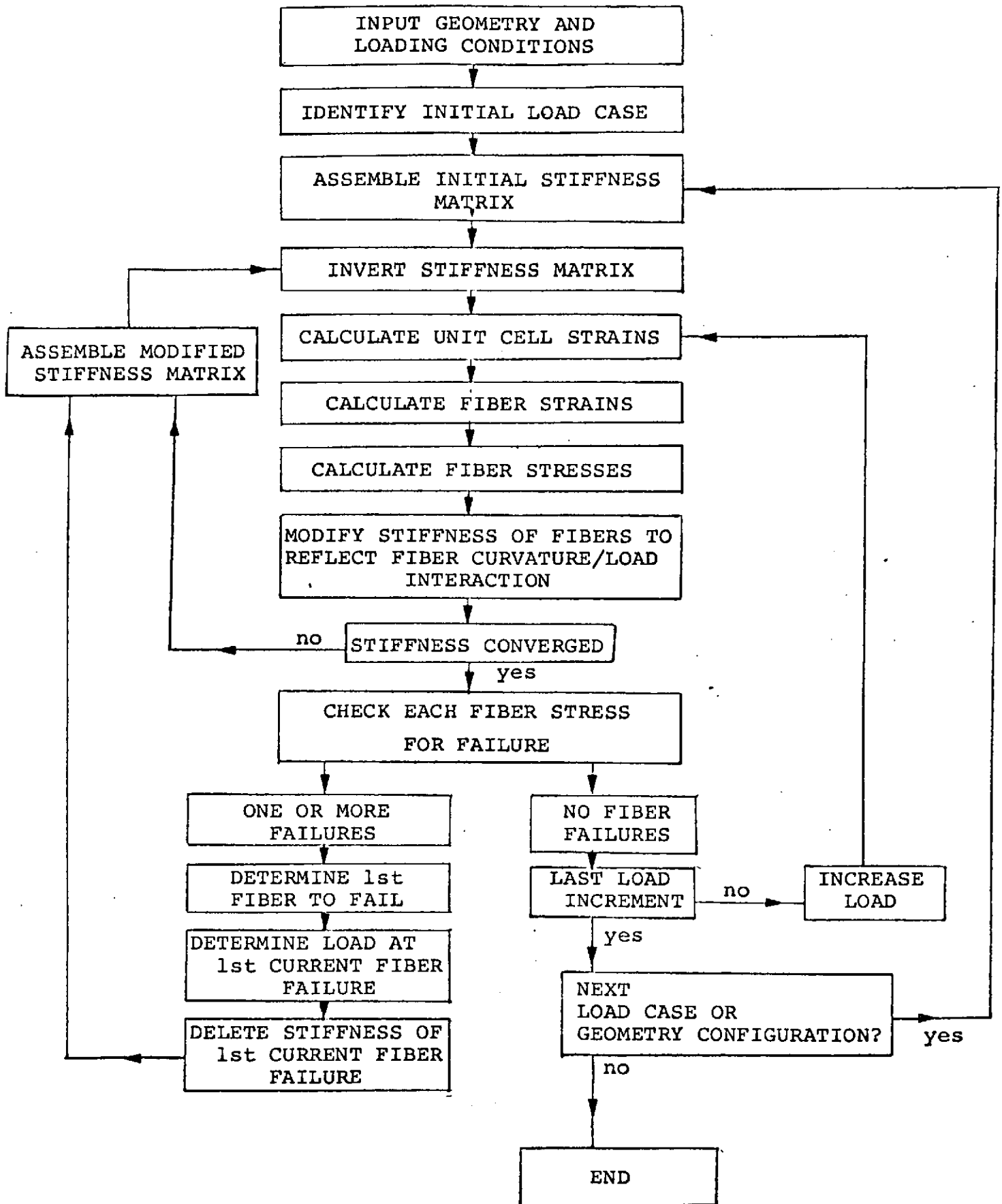


Figure B-1 - Space Flow Diagram.

## SPACE SAMPLE CASE

### APPENDIX C

The sample problem describing the input data required to model the RSI material described earlier in this report is provided here, along with the output from a typical case.

The following NAMELIST data was used to generate the RSI model and run two load cases:

```
$DATA
  NIT=20, SEPS=1.0E-03,SUPB=2.0E03,NOR=4,NTR=8,
  SGM(1,1)=40*0.4E05,
  RAT(1,1)=40*10.0E00,
  EC(1,1)=40*1.0E00,
  EY(1,1)=40*0.2E08,
  L(1,1)=40*1.0E00,
  VTI(1,1)=40*.02E-02,
  TEMP(1)=3*0.0, ALPHA=0.0,
  NB(1,1)=40*4.0E00,
  BT(1,1)=5*85.97,
  BT(1,2)=5*77.81,
  BT(1,3)=5*69.35,
  BT(1,4)=5*60.35,
  BT(1,5)=5*50.44,
  BT(1,6)=5*39.09,
  BT(1,7)=5*25.48,
  BT(1,8)=5*8.99,
  AL(1)=.0E00, 45.0E00, -45.0E00, 90.0E00,
  SGO(1,1)=1.0,0.0,0.0,0.0,0.0,0.0,
  NINC=8., MXCAL=2, SMLT=10.,
  AD=1.0, BD=1.0, DD=1.0$
$DATA
SGO(1,1)=0.0,0.0,1.0,0.0,0.0,0.0$
```

The following pages are an output listing of the above model, giving the major output data.

# SPACE FRAME MODEL 1

## MODEL GEOMETRY

DIMENSIONS OF MODEL      A = 1.00000E+00      B = 1.00000E+00      C = 1.00000E+00  
VOLUME = 1.00000E+00

NUMBER OF TRUSS ORIENTATIONS = 4  
NUMBER OF FIBER ORIENTATIONS PER TRUSS = 8

VOLUME FRACTION OF MODEL = 1.24903E+00

ORIENTATIONS TRUSS	FIBERS IN TRUSS	NUMBER OF BAYS	LENGTH OF TRUSS	VOLUME FRACTION
0.	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
-9.00000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04

## FIBER PROPERTIES

REPRODUCIBILITY OF THE  
ORIGINAL PAGE IS POOR

ORIENTATIONS TRUSS	FIBERS IN TRUSS	YOUNG'S MODULUS	ECCENT.	CROSS- SECTIONAL AREA	MAXIMUM STRESS
0.	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
0.	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
0.	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
0.	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
0.	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
0.	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
0.	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
0.	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
-4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
-4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
-4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
-4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
-4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
-4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
-4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
-4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
9.00000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
9.00000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
9.00000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
9.00000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
9.00000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
9.00000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
9.00000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
9.00000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
9.00000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
9.00000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
9.00000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
9.00000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
9.00000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
9.00000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
9.00000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
9.00000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04

## ANALYSIS

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD	STRAIN		
	11	1.00000E+00		1.41636E-04	
	22	0.		-3.81283E-05	
	33	0.		-1.36260E-05	
	12	0.		-3.11030E-13	
	23	0.		3.90976E-19	
	31	0.		-1.34076E-18	
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS

REPRODUCTION OF THIS  
ORIGINAL PAGE IS POOR



1	1	-3.69851E+02	1	2	-1.92805E+02
1	3	1.63463E+02	1	4	7.00834E+02
1	5	1.41896E+03	1	6	2.29696E+03
1	7	3.24466E+03	1	8	3.96079E+03
2	1	-3.82619E+02	2	2	-3.08066E+02
2	3	-1.58043E+02	2	4	6.82872E+01
2	5	3.70810E+02	2	6	7.40771E+02
2	7	1.14020E+03	2	8	1.44211E+03
3	1	-3.82619E+02	3	2	-3.08066E+02
3	3	-1.58043E+02	3	4	6.82872E+01
3	5	3.70810E+02	3	6	7.40771E+02
3	7	1.14020E+03	3	8	1.44211E+03
4	1	-3.95387E+02	4	2	-4.23327E+02
4	3	-4.79550E+02	4	4	-5.64369E+02
4	5	-6.77752E+02	4	6	-8.16432E+02
4	7	-9.66187E+02	4	8	-1.07940E+03
5	1	-1.07107E+03	5	2	-8.66091E+02
5	3	-4.53608E+02	5	4	1.68686E+02
5	5	1.00033E+03	5	6	2.01707E+03
5	7	3.11444E+03	5	8	3.94362E+03

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD	STRAIN		
	11	1.10000E+01		1.55050E+03	
	22	0.		-4.19227E+04	
	33	0.		-1.49514E+04	
	12	0.		-3.39379E+12	
	23	0.		5.73941E+18	
	31	0.		-1.06490E+17	
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-4.05825E+03	1	2	-2.12009E+03
1	3	1.77995E+03	1	4	7.65134E+03
1	5	1.54736E+04	1	6	2.50004E+04
1	7	3.52384E+04	1	8	4.29440E+04
2	1	-4.19812E+03	2	2	-3.38283E+03
2	3	-1.74207E+03	2	4	7.33397E+02
2	5	4.03895E+03	2	6	8.07473E+03
2	7	1.24238E+04	2	8	1.57054E+04
3	1	-4.19812E+03	3	2	-3.38283E+03
3	3	-1.74207E+03	3	4	7.33397E+02
3	5	4.03895E+03	3	6	8.07473E+03
3	7	1.24238E+04	3	8	1.57054E+04
4	1	-4.33799E+03	4	2	-4.64546E+03
4	3	-5.26415E+03	4	4	-6.19748E+03
4	5	-7.44504E+03	4	6	-8.97081E+03
4	7	-1.06183E+04	4	8	-1.18635E+04
5	1	-1.17732E+04	5	2	-9.52874E+03
5	3	-5.01110E+03	5	4	1.80604E+03
5	5	1.08927E+04	5	6	2.19517E+04
5	7	3.38269E+04	5	8	4.27586E+04

MEMBER FAILURE: TRUSS 1 FIBER A  
MEMBER FAILURE: TRUSS 5 FIBER A

REPRODUCIBILITY OF THE  
ORIGINAL PAGE IS NOT

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD		STRAIN	
	11	1.02448E+01		2.38060E+03	
	22	0.		-6.38067E+04	
	33	0.		-2.27040E+04	
	12	0.		-5.20077E+12	
	23	0.		7.35110E+18	
	31	0.		-1.96920E+17	
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-6.15839E+03	1	2	-3.18578E+03
1	3	2.79563E+03	1	4	1.17903E+04
1	5	2.37521E+04	1	6	3.82882E+04
1	7	5.38704E+04	1	8	0.
2	1	-6.37271E+03	2	2	-5.12078E+03
2	3	-2.60118E+03	2	4	1.20036E+03
2	5	6.27354E+03	2	6	1.24615E+04
2	7	1.91224E+04	2	8	2.41435E+04
3	1	-6.37271E+03	3	2	-5.12078E+03
3	3	-2.60118E+03	3	4	1.20036E+03
3	5	6.27354E+03	3	6	1.24615E+04
3	7	1.91224E+04	3	8	2.41435E+04
4	1	-6.58703E+03	4	2	-7.05551E+03
4	3	-7.99820E+03	4	4	-9.42025E+03
4	5	-1.13210E+04	4	6	-1.36455E+04
4	7	-1.61552E+04	4	8	-1.80521E+04
5	1	-1.79121E+04	5	2	-1.44737E+04
5	3	-7.55214E+03	5	4	2.89387E+03
5	5	1.67954E+04	5	6	3.36705E+04
5	7	5.17385E+04	5	8	0.
MEMBER FAILURE: TRUSS 1 FIBER 7					

MEMBER FAILURE! TRUSS 1 FIBER 7

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD		STRAIN	
	11		1.02448E+01		3.04913E+03
	22		0.		-8.27776E+04
	33		0.		-2.59670E+04
	12		0.		-6.61388E+12
	23		0.		9.12515E+18
	31		0.		-1.96952E+17
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-6.99689E+03	1	2	-3.22510E+03
1	3	4.36246E+03	1	4	1.57600E+04
1	5	3.08969E+04	1	6	4.92602E+04
1	7	0.	1	8	0.
2	1	-7.27213E+03	2	2	-5.71018E+03
2	3	-2.56656E+03	2	4	2.17590E+03
2	5	8.50065E+03	2	6	1.62099E+04
2	7	2.45021E+04	2	8	3.07484E+04
3	1	-7.27213E+03	3	2	-5.71018E+03
3	3	-2.56656E+03	3	4	2.17590E+03
3	5	8.50065E+03	3	6	1.62099E+04
3	7	2.45021E+04	3	8	3.07484E+04

4	1	-7.54736E+03	4	2	-8.19484E+03
4	3	-9.49767E+03	4	4	-1.14629E+04
4	5	-1.40896E+04	4	6	-1.73017E+04
4	7	-2.07695E+04	4	8	-2.33904E+04
5	1	-2.32389E+04	5	2	-1.88245E+04
5	3	-9.93713E+03	5	4	3.47757E+03
5	5	2.13090E+04	5	6	4.29090E+04
5	7	6.59820E+04	5	8	0.

MEMBER FAILURE: TRUSS 5 FIBER 7

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD	STRAIN		
	11	1.02448E+01		4.11875E-03	
	22	0.		-1.03387E-03	
	33	0.		-3.62777E-04	
	12	0.		-8.99540E-12	
	23	0.		1.27385E-17	
	31	0.		-2.23711E-17	
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	-9.79426E+03	1	2	-4.68641E+03
1	3	5.58877E+03	1	4	2.10013E+04
1	5	4.14241E+04	1	6	6.61308E+04
1	7	0.	1	8	0.
2	1	-1.01600E+04	2	2	-7.98879E+03
2	3	-3.61865E+03	2	4	2.97420E+03
2	5	1.17588E+04	2	6	2.24521E+04
2	7	3.39367E+04	2	8	4.25760E+04
3	1	-1.01600E+04	3	2	-7.98879E+03
3	3	-3.61865E+03	3	4	2.97420E+03
3	5	1.17588E+04	3	6	2.24521E+04
3	7	3.39367E+04	3	8	4.25760E+04
4	1	-1.05257E+04	4	2	-1.12904E+04
4	3	-1.28291E+04	4	4	-1.51500E+04
4	5	-1.82519E+04	4	6	-2.20451E+04
4	7	-2.61399E+04	4	8	-2.92347E+04
5	1	-2.89745E+04	5	2	-2.31098E+04
5	3	-1.13004E+04	5	4	6.52201E+03
5	5	3.01517E+04	5	6	5.86875E+04
5	7	0.	5	8	0.

MEMBER FAILURE: TRUSS 1 FIBER 6

# SPACE FRAME MODEL 2 -----

## MODEL GEOMETRY -----

DIMENSIONS OF MODEL      A = 1.00000E+00      B = 1.00000E+00      C = 1.00000E+00  
 VOLUME = 1.00000E+00

NUMBER OF TRUSS ORIENTATIONS = 4  
 NUMBER OF FIBER ORIENTATIONS PER TRUSS = 8

VOLUME FRACTION OF MODEL = 1.24903E+00

ORIENTATIONS TRUSS	FIBERS IN TRUSS	NUMBER OF BAYS	LENGTH OF TRUSS	VOLUME FRACTION
0.	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
0.	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
-4.50000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.59700E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	7.78100E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.93500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	6.03500E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	5.04400E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	3.90900E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	2.54800E+01	4.00000E+00	1.00000E+00	2.00000E-04
9.00000E+01	8.99000E+00	4.00000E+00	1.00000E+00	2.00000E-04

FIBER PROPERTIES

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REPRODUCIBILITY OF THE  
 ORIGINAL PAGE IS POOR

ORIENTATIONS TRUSS	FIBERS IN TRUSS	YOUNG'S MODULUS	ECCEN <sup>1</sup> .	CROSS- SECTIONAL AREA	MAXIMUM STRESS
0.	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
0.	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
0.	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
0.	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
0.	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
0.	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
0.	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
0.	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
-4.50000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
-4.50000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
-4.50000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
-4.50000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
-4.50000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
-4.50000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
-4.50000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
-4.50000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
9.00000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
9.00000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
9.00000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
9.00000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
9.00000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
9.00000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
9.00000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
9.00000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04
9.00000E+01	8.59700E+01	2.00000E+07	1.00000E+00	2.48463E-02	4.00000E+04
9.00000E+01	7.78100E+01	2.00000E+07	1.00000E+00	2.75239E-03	4.00000E+04
9.00000E+01	6.93500E+01	2.00000E+07	1.00000E+00	9.86737E-04	4.00000E+04
9.00000E+01	6.03500E+01	2.00000E+07	1.00000E+00	5.01447E-04	4.00000E+04
9.00000E+01	5.04400E+01	2.00000E+07	1.00000E+00	3.02543E-04	4.00000E+04
9.00000E+01	3.90900E+01	2.00000E+07	1.00000E+00	2.03710E-04	4.00000E+04
9.00000E+01	2.54800E+01	2.00000E+07	1.00000E+00	1.50587E-04	4.00000E+04
9.00000E+01	8.99000E+00	2.00000E+07	1.00000E+00	1.25790E-04	4.00000E+04

# ANALYSIS -----

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD	STRAIN		
	11	0.	-1.36294E-05		
	22	0.	-9.37055E-06		
	33	1.00000E+00	4.78628E-05		
	12	0.	8.52167E-14		
	23	0.	-4.04352E-19		
	31	0.	-1.61782E-18		
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS

1	1	1.36743E+03	1	2	1.29735E+03
1	3	1.15633E+03	1	4	9.43570E+02
1	5	6.59110E+02	1	6	3.11143E+02
1	7	-6.46903E+01	1	8	-3.48819E+02
2	1	1.36773E+03	2	2	1.30008E+03
2	3	1.16395E+03	2	4	9.58552E+02
2	5	6.83953E+02	2	6	3.48033E+02
2	7	-1.47783E+01	2	8	-2.89069E+02
3	1	1.36773E+03	3	2	1.30008E+03
3	3	1.16395E+03	3	4	9.58552E+02
3	5	6.83953E+02	3	6	3.48033E+02
3	7	-1.47782E+01	3	8	-2.89069E+02
4	1	1.36803E+03	4	2	1.30281E+03
4	3	1.17156E+03	4	4	9.73533E+02
4	5	7.08780E+02	4	6	3.84923E+02
4	7	3.51336E+01	4	8	-2.29318E+02
5	1	-2.70118E+02	5	2	-2.74974E+02
5	3	-2.84747E+02	5	4	-2.99490E+02
5	5	-3.19198E+02	5	6	-3.43304E+02
5	7	-3.69335E+02	5	8	-3.89013E+02

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD	STRAIN		
	11	0.		-1.49926E-04	
	22	0.		-1.03068E-04	
	33	1.10000E+01		5.25434E-04	
	12	0.		9.36965E-13	
	23	0.		-4.40999E-18	
	31	0.		-1.46045E-17	
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	1.49611E+04	1	2	1.41965E+04
1	3	1.26570E+04	1	4	1.03323E+04
1	5	7.22048E+03	1	6	3.40784E+03
1	7	-7.17243E+02	1	8	-3.83735E+03
2	1	1.49644E+04	2	2	1.42263E+04
2	3	1.27403E+04	2	4	1.04963E+04
2	5	7.49282E+03	2	6	3.81307E+03
2	7	-1.68108E+02	2	8	-3.18010E+03
3	1	1.49644E+04	3	2	1.42263E+04
3	3	1.27403E+04	3	4	1.04963E+04
3	5	7.49282E+03	3	6	3.81307E+03
3	7	-1.68108E+02	3	8	-3.18010E+03
4	1	1.49677E+04	4	2	1.42562E+04
4	3	1.28236E+04	4	4	1.06604E+04
4	5	7.76514E+03	4	6	4.21821E+03
4	7	3.81007E+02	4	8	-2.52281E+03
5	1	-2.97079E+03	5	2	-3.02421E+03
5	3	-3.13171E+03	5	4	-3.29389E+03
5	5	-3.51068E+03	5	6	-3.77584E+03
5	7	-4.06217E+03	5	8	-4.27863E+03

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

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DIRECTION		APPLIED LOAD		STRAIN	
	11	0.			-2.86225E-04
	22	0.			-1.96750E-04
	33	2.10000E+01			1.00109E-03
	12	0.			1.78831E-12
	23	0.			-7.83209E-18
	31	0.			-2.81076E-17
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	2.84103E+04	1	2	2.69622E+04
1	3	2.40452E+04	1	4	1.96365E+04
1	5	1.37281E+04	1	6	6.47792E+03
1	7	-1.38003E+03	1	8	-7.32647E+03
2	1	2.84166E+04	2	2	2.70188E+04
2	3	2.42033E+04	2	4	1.99483E+04
2	5	1.42464E+04	2	6	7.25045E+03
2	7	-3.31490E+02	2	8	-6.07173E+03
3	1	2.84166E+04	3	2	2.70188E+04
3	3	2.42033E+04	3	4	1.99483E+04
3	5	1.42464E+04	3	6	7.25045E+03
3	7	-3.31490E+02	3	8	-6.07173E+03
4	1	2.84220E+04	4	2	2.70755E+04
4	3	2.43614E+04	4	4	2.02601E+04
4	5	1.47646E+04	4	6	8.02268E+03
4	7	7.16983E+02	4	8	-4.81687E+03
5	1	-5.67053E+03	5	2	-5.77252E+03
5	3	-5.97775E+03	5	4	-6.28737E+03
5	5	-6.70125E+03	5	6	-7.20745E+03
5	7	-7.75407E+03	5	8	-8.16728E+03

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD		STRAIN	
	11	0.		-4.22527E-04	
	22	0.		-2.90417E-04	
	33	3.10000E+01		1.47484E-03	
	12	0.		2.63917E-12	
	23	0.		-1.28818E-17	
	31	0.		-5.00643E-17	
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	4.17181E+04	1	2	3.95972E+04
1	3	3.53228E+04	1	4	2.88574E+04
1	5	2.01826E+04	1	6	9.52159E+03
1	7	-2.05301E+03	1	8	-1.08162E+04
2	1	4.17273E+04	2	2	3.96803E+04
2	3	3.55550E+04	2	4	2.93158E+04
2	5	2.09454E+04	2	6	1.06604E+04
2	7	-5.04876E+02	2	8	-8.96395E+03
3	1	4.17273E+04	3	2	3.96803E+04
3	3	3.55550E+04	3	4	2.93158E+04
3	5	2.09454E+04	3	6	1.06604E+04
3	7	-5.04876E+02	3	8	-8.96395E+03
4	1	4.17364E+04	4	2	3.97634E+04
4	3	3.57872E+04	4	4	2.97740E+04
4	5	2.17080E+04	4	6	1.17084E+04

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4	7	1.04311E+03	4	8	-7.11148E+03
5	1	-8.36933E+03	5	2	-8.51989E+03
5	3	-8.82286E+03	5	4	-9.27992E+03
5	5	-9.89088E+03	5	6	-1.06381E+04
5	7	-1.14450E+04	5	8	-1.20549E+04

MEMBER FAILURE: TRUSS 1 FIBER 1  
 MEMBER FAILURE: TRUSS 2 FIBER 1  
 MEMBER FAILURE: TRUSS 3 FIBER 1  
 MEMBER FAILURE: TRUSS 4 FIBER 1

SOLUTION FOR STRESS CONVERGES IN 2 ITERATIONS

DIRECTION		APPLIED LOAD		STRAIN	
	11	0.			-5.58636E-04
	22	0.			-3.83935E-04
	33	2.96957E+01			1.95566E-03
	12	0.			3.48834E-12
	23	0.			-1.26954E-17
	31	0.			-4.24687E-17
TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	0.	1	2	5.23447E+04
1	3	4.67136E+04	1	4	3.81892E+04
1	5	2.67383E+04	1	6	1.26444E+04
1	7	-2.68378E+03	1	8	-1.42946E+04
2	1	0.	2	2	5.24539E+04
2	3	4.70190E+04	2	4	3.87925E+04
2	5	2.77438E+04	2	6	1.41479E+04
2	7	-6.36594E+02	2	8	-1.18458E+04
3	1	0.	3	2	5.24539E+04
3	3	4.70190E+04	3	4	3.87925E+04
3	5	2.77438E+04	3	6	1.41479E+04
3	7	-6.36594E+02	3	8	-1.18458E+04
4	1	0.	4	2	5.25630E+04
4	3	4.73243E+04	4	4	3.93957E+04
4	5	2.87488E+04	4	6	1.56504E+04
4	7	1.41031E+03	4	8	-9.39659E+03
5	1	-1.10633E+04	5	2	-1.12624E+04
5	3	-1.16630E+04	5	4	-1.22673E+04
5	5	-1.30750E+04	5	6	-1.40629E+04
5	7	-1.51297E+04	5	8	-1.59360E+04

MEMBER FAILURE: TRUSS 1 FIBER 2  
 MEMBER FAILURE: TRUSS 2 FIBER 2  
 MEMBER FAILURE: TRUSS 3 FIBER 2  
 MEMBER FAILURE: TRUSS 4 FIBER 2

SOLUTION FOR STRESS CONVERGES IN 3 ITERATIONS

DIRECTION		APPLIED LOAD		STRAIN	
	11	0.			-8.22897E-04
	22	0.			-5.65390E-04
	33	2.96957E+01			2.99701E-03
	12	0.			5.13656E-12
	23	0.			-1.47088E-17

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TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
1	1	0.	1	2	0.
1	3	7.12752E+04	1	4	5.84641E+04
1	5	4.12136E+04	1	6	1.99150E+04
1	7	-3.33460E+03	1	8	-2.09701E+04
2	1	0.	2	2	0.
2	3	7.17200E+04	2	4	5.93446E+04
2	5	4.26851E+04	2	6	2.21229E+04
2	7	-3.17130E+02	2	8	-1.73622E+04
3	1	0.	3	2	0.
3	3	7.17200E+04	3	4	5.93446E+04
3	5	4.26851E+04	3	6	2.21229E+04
3	7	-3.17130E+02	3	8	-1.73622E+04
4	1	0.	4	2	0.
4	3	7.21646E+04	4	4	6.02248E+04
4	5	4.41555E+04	4	6	2.43284E+04
4	7	2.69891E+03	4	8	-1.37533E+04
5	1	-1.62891E+04	5	2	-1.65825E+04
5	3	-1.71727E+04	5	4	-1.80630E+04
5	5	-1.92531E+04	5	6	-2.07086E+04
5	7	-2.22801E+04	5	8	-2.34681E+04

MEMBER FAILURE: TRUSS 4 FIBER 3

SOLUTION FOR STRESS CONVERGES IN 3 ITERATIONS

TRUSS	DIRECTION	APPLIED LOAD	STRAIN	TRUSS	ORIENTATIONS FIBERS IN TRUSS	STRESS
	11	0.	-9.46584E+04	1	2	0.
	22	0.	-5.77144E+04	1	4	6.53154E+04
	33	2.94957E+01	3.36218E-03	1	6	2.19268E+04
	12	0.	5.02068E-12	1	8	-2.41791E+04
	23	0.	-1.37373E-17	2	2	0.
	31	0.	-7.05499E-17	2	4	6.65744E+04
				2	6	2.50905E+04
				2	8	-1.90039E+04
				3	2	0.
				3	4	6.65744E+04
				3	6	2.50905E+04
				3	8	-1.90039E+04
				4	2	0.
				4	4	6.78326E+04
				4	6	2.82493E+04
				4	8	-1.38266E+04
				5	2	-1.70635E+04
				5	4	-1.91875E+04
				5	6	-2.29826E+04
				5	8	-2.69407E+04

MEMBER FAILURE: TRUSS 2 FIBER 3

## SPACE PROGRAM LISTING

### APPENDIX D

The following pages present a listing of the CDC 6600 version of the SPACE program. The program is written for a "RUN" compiler, and requires 70K of core to compile and execute. The compilation of the program and execution of the sample case given in Appendix C required less than 13 system seconds of time.



48.

RUN VERSION 2.3 --PSR LEVEL 363--

MAIN

08/22/74

```

      C      INPUT PER CASE
      C
      C      CONTROL PARAMETERS
000137      32 NORP= NOR + 1
      C
      C      RESET MATRIX STO TO ZERO
      C
000141      DO 19 KDF=1,5
000143      DO 19 KDZ=1,30
000144      19 STO(KDF,KDZ)=0
      C      MODEL GEOMETRY
      C      STRESS LIMIT
      C      FIBER AND TRUSS PROPERTIES
      C      ANGULAR ORIENTATIONS
      C      INITIAL LOADING
      C
      C
      C      INITIAL COMPUTATIONS AND ASSIGNMENTS
000152      DO 440 I=1,NORP
000154      DO 440 J=1,NTR
000155      IFAIL(I,J) = .FALSE.
000160      440 CONTINUE
000164      MSINGD = .FALSE.
000165      INC = 0
000166      IT = 0
000167      ITOT = 0
000170      MEMB = 1
000171      VMOD = 0.0E 00
000172      KNT = NORP*NTR
000174      V = AD*RD*DD
000177      DO 480 I=1,6
000200      SM(I) = SMLT*SGO(I,1)
000202      SLN(I,1) = 0.0E 00
000203      480 CONTINUE
      C
      C
000205      DO 910 I=1,NORP
000206      DO 910 J=1,NTR
000207      IF (INP.EQ.2) GO TO 890
000211      DM(I,J) = L(I,J)*DSEC(RAD(RT(I,J)))/(2.0*NB(I,J)*KAT(I,J))
000227      ETA(I,J) = 4.*NB(I,J)**2*DD/(L(I,J)* TAN(RAD(BT(I,J))))
000242      890 CONTINUE
000242      A(I,J) = PI*DM(I,J)**2/4.0E0
000251      VT(I,J) = 2.*NR(I,J)*A(I,J)/( SIN(RAD(RT(I,J)))*AD*BD)
000256      FRAC(I,J) = VT(I,J)/VT(I,J)
000272      VMOD = VMOD + VT(I,J)
000274      910 CONTINUE
      C
      C      PRINT OUT INPUT INFORMATION
000300      CALL INPUT(NUR,NTR,ICS, AL, RT)
      C
      C
      C      DEGREE TO RADIAN CONVERSION
000304      DO 912 I=1,NUR
000306      AL(I) = RAD(AL(I))

```

```

000312 912 CONTINUE
000315 DO 913 I=1,NORP
000316 DO 913 J=1,NTR
000317 BT(I,J) = RAD(BT(I,J))
000324 913 CONTINUE
C
C RETURN TO 915 TO INCREMENT LOADING
000331 915 CONTINUE
C E* AT ALPHA = 0
000331 DO 917 I=1,NORP
000333 DO 917 J=1,NTR
000334 IF(IFAIL(I,J)) GO TO 917
000337 DE(I,J) = EY(I,J)/(8.0E0* EC(I,J)**2+1.0E0)
000347 917 CONTINUE
C RETURN TO 920 FOR NEXT ITERATIVE STEP
C INITIALIZE MATRICES D + E TO ZERO
000354 920 CONTINUE
000354 DO 950 M=1,6
000356 DO 950 N=1,6
000357 D(M,N) = 0.0E 00
000362 F(M,N) = 0.0E0
000365 950 CONTINUE
C
C
000371 DO 1005 I=1,6
000372 TRMO(I,1) = V*SGO(I,1)
000375 1005 CONTINUE
C EVALUATE MATRICES D + E+ FIRST FOR +BETA + SECONDLY FOR -BETA
000376 PSBT = .TRUE.
000377 GO TO 1020
000400 1010 CONTINUE
000400 DO 1015 I=1,NORP
000402 DO 1015 J=1,NTR
000403 BT(I,J) = -BT(I,J)
000406 1015 CONTINUE
000413 PSBT = .FALSE.
000414 1020 CONTINUE
C
000414 DO 1750 I=1,NOR
000416 DO 1750 J=1,NTR
000417 IF(IFAIL(I,J)) GO TO 1750
C SET PRELIMINARY VALUE OF MATRIX ELEMENTS
000422 PP = ETA(I,J)*DM(I,J)*RAT(I,J)*A(I,J)/2.*FRAC(I,J)
000433 SNA = SIN(AL(I))
000436 SN2A = SIN(2.*AL(I))
000443 SNA2 = SNA**2
000444 SNA3 = SNA2*SNA
000445 SN2A2 = SN2A**2
000447 SNA4 = SNA2**2
000450 SNR2 = SIN(BT(I,J))**2
000454 SNB4 = SNR2**2
000455 SN2B = SIN(2.*BT(I,J))
000463 SN2B2 = SN2B**2
000464 CSA = COS(AL(I))
000467 CSA2 = CSA**2

```

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ORIGINAL PAGE IS POOR

```

000470      CSA3 = CSA2*CSA
000471      CSA4 = CSA2**2
000472      CSB2 = COS(BT(I,J))**2
000476      CSB4 = CSB2**2

      C
      C      ELEMENTS OF D MATRIX
000477      C( 1,I,J) = PP*CSA4*CSB4
000506      C( 2,I,J) = PP*CSA2*SNA2*CSB4
000515      C( 3,I,J) = PP*CSA2*CSB2*SNB2
000525      C( 4,I,J) = -PP*CSA2*SN2A*CSB4
000535      C( 5,I,J) = -PP*CSA2*SNA*CSB2*SN2B
000547      C( 6,I,J) = -PP*CSA3*CSB2*SN2B
000557      C( 7,I,J) = PP*CSB4*SNA4
000567      C( 8,I,J) = PP*CSB2*SNB2*SNA2
000575      C( 9,I,J) = -PP*CSB4*SNA2*SN2A
000605      C(10,I,J) = -PP*SNA3*CSB2*SN2B
000615      C(11,I,J) = -PP*CSA*SNA2*CSB2*SN2B
000627      C(12,I,J) = PP*SNB4
000635      C(13,I,J) = -PP*SN2A*CSB2*SNB2
000644      C(14,I,J) = -PP*SNA*SNB2*SN2B
000654      C(15,I,J) = -PP*CSA*SNB2*SN2B
000665      C(16,I,J) = PP*SN2A2*CSB4
000674      C(17,I,J) = PP*SNA*SN2A*CSB2*SN2B
000704      C(18,I,J) = PP*CSA*SN2A*CSB2*SN2B
000715      C(19,I,J) = PP*SNA2*SN2B2
000724      C(20,I,J) = PP*SNA*CSA*SN2R2
000733      C(21,I,J) = PP*CSA2*SN2B2
000742      1750 CONTINUE

      C
      C      FORM UPPER TRIANGLE OF D MATRIX
000747      MC = 0
000750      DO 1800 M=1,6
000751      DO 1800 N=M,6
000752      MC = MC + 1
000754      DO 1800 I=1,NOR
000755      DO 1800 J=1,NTR
000756      IF(IFAIL(I,J)) GO TO 1800
000761      D(M,N) = D(M,N) + C( MC,I,J)*DE(I,J)
000774      1800 CONTINUE

      C
      C      FORM SYMMETRIC ELEMENTS OF D
001005      DO 1850 M=2,6
001007      LD = M-1
001011      DO 1850 N=1,LD
001012      D(M,N) = D(N,M)
001017      1850 CONTINUE

      C
      I = NORP
001023      DO 1900 J=1,NTR
001025      IF(IFAIL(I,J)) GO TO 1900
001026      PP = ETA(I,J)*DM(I,J)*RAT(I,J)*A(I,J)/2.*FRAC(I,J)
001031      SNB2 = SIN(BT(I,J))**2
001042      SNB4 = SNB2**2
001046      SN2R = SIN(2.*BT(I,J))
001047      SN2R2 = SN2R**2
001055

```

MUN VERSTON 2.3 --PSH LEVEL 363--

MAIN

08/72/74

```

001056      CSB2 = COS(BT(I,J))*2
001062      CSB4 = CSB2**2
      C
      C      ELEMENTS OF E MATRIX
001063      G( 1,I,J) = PP*CSB4
001071      G( 2,I,J) = PP*CSB2*SNB2
001076      G( 3,I,J) = -PP*CSB2*SN2B
001102      G( 4,I,J) = PP*SNB4
001106      G( 5,I,J) = -PP*SNB2*SN2B
001113      G( 6,I,J) = PP*SN2B2
001117      1900 CONTINUE
      C
      C      FORM UPPER TRIANGLE OF E MATRIX
001122      DO 1910 J=1,NTR
001123      IF(FAIL(I,J)) GO TO 1910
001126      E(1,1) = E(1,1) + G( 1,I,J)*DE(I,J)
001134      E(1,2) = E(1,2) + G( 2,I,J)*DE(I,J)
001143      E(1,4) = E(1,4) + G( 3,I,J)*DE(I,J)
001151      E(2,2) = E(2,2) + G( 4,I,J)*DE(I,J)
001160      E(2,4) = E(2,4) + G( 5,I,J)*DE(I,J)
001166      E(4,4) = E(4,4) + G( 6,I,J)*DE(I,J)
001175      1910 CONTINUE
      C
      C      FORM SYMMETRIC ELEMENTS OF E
001200      E(2,1) = E(1,2)
001201      E(4,1) = E(1,4)
001203      E(4,2) = E(2,4)
      C
      C      CHECK FOR +BETA OR -BETA
001204      IF(PSBT) GO TO 1010
001206      DO 1915 I=1,NORP
001207      DO 1915 J=1,NTR
001210      RT(I,J) = -BT(I,J)
001213      1915 CONTINUE
      C
      C      FORM SUM OF MATRICES D + E
001220      1917 CONTINUE
001220      DO 1920 M=1,6
001222      DO 1920 N=1,6
001223      Z(M,N) = D(M,N) + E(M,N)
001232      1920 CONTINUE
001236      IF(MSINGD) GO TO 1967
      C
      C
      C      INVERT RESULTANT MATRIX
001237      CALL INVRTD(Z,6,6,DET,1,E=15,IRANK,1.00E-50)
      C
      C      CHECK FOR SINGULAR MATRIX
001246      IF(IRANK.EQ.6) GO TO 1968
001250      MSINGD = .TRUE.
001251      WRITE(6,9710) IRANK,DET
001260      GO TO 1917
001261      1967 CONTINUE
001261      WRITE(6,9715) ((Z(K1,L1),L1=1,6),K1=1,6)
001277      MSINGD = .FALSE.

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001300      GO TO 7000
001301      1968 CONTINUE
      C
      C      STRESS CALCULATIONS
001301      2000 CONTINUE
001301      DO 4000 I=1,NORP
001303      DO 4000 J=1,NTR
001304      IF(IFAIL(I,J)) GO TO 4000
001307      IF(I.EQ.NORP) GO TO 2050
001311      SNA = SIN(AL(I))
001313      SNA2 = SNA**2
001314      SN2A = SIN(2.*AL(I))
001321      CSA = COS(AL(I))
001324      CSA2 = CSA**2
001325      2050 CONTINUE
001325      SN2B = SIN(2.*BT(I,J))
001334      SNB2 = SIN(BT(I,J))**2
001340      CSB2 = COS(BT(I,J))**2
001345      IF(I.EQ.NORP) GO TO 2080
      C
      C      STRESS-STRAIN FACTORS
001347      TRIG(1,1) = CSA2*CSB2
001351      TRIG(1,2) = CSB2*SNA2
001353      TRIG(1,3) = SNB2
001354      TRIG(1,4) = -SN2A*CSB2
001356      TRIG(1,5) = -SNA*SN2B
001360      TRIG(1,6) = -CSA*SN2B
001361      2080 CONTINUE
      C
      C      STORE STRESS VALUE FROM PREVIOUS ITERATION
001361      IF(IT.EQ.0) GO TO 3110
001362      SGP(I,J) = SGF(I,J)
001367      3110 CONTINUE
      C      CALCULATE STRAIN VALUES
001367      CALL MXMULU(Z,TRMO,EV,6,6,1,6,6,1)
001400      DO 3115 ITMP=1,3
001402      EV(ITMP,1) = EV(ITMP,1) + .5*ALPHA*TEMP(ITMP)
001407      3115 CONTINUE
001410      CALL MXMULD(TRIG,EV,DIRF,1,6,1,1,6,1)
001421      COMD = DIRF(1,1)
001423      TRIG(1,5) = -TRIG(1,5)
001424      TRIG(1,6) = -TRIG(1,6)
001425      CALL MXMULD(TRIG,EV,DIRF,1,6,1,1,6,1)
001435      IF(ABS(COMD).LE.ABS(DIRF(1,1))) GO TO 3201
001442      DIRF(1,1) = COMD
001442      3201 IF(I.LT.NORP) GO TO 3525
      C      CALCULATE STRESS VALUES
001445      SGF(I,J) = EP(I,J)*(EV(1,1)*CSR2*EV(2,1)*SNR2*EV(4,1)*SN2B)
001460      COMD = EP(I,J)*(EV(1,1)*CSR2*EV(2,1)*SNR2*EV(4,1)*SN2B)
001470      IF(ABS(COMD).LE.ABS(SGF(I,J))) GO TO 3202
001476      SGF(I,J) = COMD
001500      3202 GO TO 3550
001501      3525 CONTINUE
001501      SGF(I,J) = EP(I,J)*DIRF(1,1)

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001507 3550 CONTINUE
001507 ALP = 16.*SGF(I,J)/(PI**2*EY(I,J))*(RAT(I,J))**2
001522 ABSA = ABS(ALP)
001523 IF(SGF(I,J).LE.0.0E 00) EP(I,J) = EVAL(EY(I,J),ABSA,EC(I,J),
1 CUEL(EC(I,J),ABSA))
001543 IF(SGF(I,J).GT.0.0E 00) EP(I,J) = EVAL(EY(I,J),ABSA,EC(I,J),
1 TDEL(EC(I,J),ABSA))
001563 4000 CONTINUE
C
C STRESS CONVERGENCE TEST
001570 IF(IT.NE.0) GO TO 4010
001571 IT = 1
001572 GO TO 920
001573 4010 CONTINUE
001573 DO 5000 I=1,NORP
001575 DO 5000 J=1,NTR
001576 IF(IFAIL(I,J)) GO TO 5000
001601 DSG = ABS(SGF(I,J)-SGP(I,J))
C CHECK FOR ZERO STRESS OR RELATIVE STRESS .LT. 1.D-06
001606 IF((SGP(I,J).EQ.0.).OR.(DSG.LT.1.E-06)) GO TO 4800
001617 DSG = ABS(DSG/SGP(I,J))
001621 4800 CONTINUE
001621 IF(DSG.LT.SEPS) GO TO 5000
001624 IF(DSG.GT.SUPB) GO TO 4900
C STRESS ITERATION
001627 IT = IT + 1
001630 IF(IT.LT.NIT) GO TO 920
C NO CONVERGENCE WITHIN ITERATION LIMIT
001632 ICON = 1
001633 GO TO 5100
C DIVERGENCE
001634 4900 ICON = 2
001635 GO TO 5100
001636 5000 CONTINUE
C NORMAL CONVERGENCE
001643 ICON = 3
001644 5100 GO TO(5200,5250,5300),ICON
C
C NON-CONVERGENCE DUMP
001653 5200 CONTINUE
001653 CALL CDUMP(NORP,NTR,ICON,IT,SGF,SGP)
001657 GO TO 7000
C
C DIVERGENCE DUMP
001660 5250 CONTINUE
001660 CALL CDUMP(NORP,NTR,ICON,IT,SGF,SGP)
001664 GO TO 7000
C
C CONVERGED SOLUTION ANALYSIS
C
001665 5300 CONTINUE
001665 WRITE(6,9720) IT
C CHECK! INCRIMENTATION LIMIT
001673 IF(INC.GE.NINC) GO TO 7000
001676 INC = INC + 1

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```

001677      IT = 0
C
C      STORE LOADINGS FOR PRESENT AND PREVIOUS INCRIMENTATIONS
001700      IF(MEMB.NE.1) GO TO 5955
001702      DO 5950 I=1,6
001703      SLP(I,1) = SLN(I,1)
001705      SLN(I,1) = SGO(I,1)
001706      5950 CONTINUE
C
C
C      COMPUTE MAXIMUM STRESS COMPARISON TERM FOR EACH MEMBER
001710      5955 CONTINUE
001710      DO 5960 I=1,NORP
001712      DO 5960 J=1,NTR
001713      IF(IFAIL(I,J)) GO TO 5960
001716      ALP = 16.*SGF(I,J)/(PI**2*EY(I,J))*(RAT(I,J))**2
001730      ALB = ABS(ALP)
001731      TRM2 = PI*EY(I,J)*EC(I,J)*U(ALB)/RAT(I,J)**2
001742      IF(SGF(I,J).LE.0.0E 00) SGC(I,J) = SGF(I,J) + 8.*SGF(I,J)*
1      (CDEL(EC(I,J),ALB)+EC(I,J)) + ALB*TRM2/
2      ((1.-ALB)*TAN(U(ALB)))
001774      IF(SGF(I,J).GT.0.0E 00) SGC(I,J) = SGF(I,J) + 8.*SGF(I,J)*
1      (-TDEL(EC(I,J),ALB)+EC(I,J)) - ALB*TRM2/
2      ((1.+ALB)*TANH(U(ALB)))
002026      5960 CONTINUE
C
002033      5975 CONTINUE
002033      5977 CONTINUE
C
C      STRESS-STRAIN OUTPUT FOR THIS LOADING
002033      CALL OUTPSS(NORP,NTR,SGO,SGC,EV)
002037      IF(INC.EQ.1) GO TO 6060
C
C      RETAIN NUMBER OF FAILED MEMBERS
002041      IRT = ITOT
C
C      CHECK COMPUTED STRESS AGAINST MAXIMUM ALLOWABLE STRESS
002043      6000 CONTINUE
002043      K = 0
002044      DO 6050 I=1,NORP
002046      DO 6050 J=1,NTR
002047      IF(IFAIL(I,J)) GO TO 6050
002052      IF(ABS(SGC(I,J)).LT.SGM(I,J)) GO TO 6050
C
C      STORE TEMPORARILY MEMBERS FAILING UNDER APPLIED LOAD INCREMENT
002061      K = K + 1
002062      TMPFL(I,J,K) = ABS(SGC(I,J))
002071      II(K) = I
002072      JJ(K) = J
002074      6050 CONTINUE
002101      IF (K.EQ.0) GO TO 6051
C
C      FIND FIRST FAILED MEMBER (OR MEMBERS)
002102      CALL RESET(TMPFL,K,IFAIL,SGM,II,JJ,KMAX,ITOT,MEMB,1.00E-02)
1      MXCAL,ISENT)
002116      IF (ISENT.EQ.1) GO TO 7000
C
C      RETAIN SLOPE TERMS (IN TERMS OF FIRST FAILED MEMBER)
C      FOR INTERPOLATION ROUTINE

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002120      IM=I(KMAX)
002122      JM=J(KMAX)
002124      SGDEL=ABS(SGC(IM,JM)-STORS(IM,JM))
002132      SMDEL=SGM(IM,JM)-ABS(STORS(IM,JM))
      C
      C CHECK SENTINELS GOVERNING FAILURE ANALYSIS
002136      6051 CONTINUE
002136      IF((ITOT.EQ.IRT).AND.(MEMB.EQ.2)) GO TO 6052
      C      .T. ---E NO FURTHER FAILURES AFTER FIRST REEVALUATION
002146      IF(.NOT.((ITOT.EQ.IRT).AND.(MEMB.EQ.3))) GO TO 6060
      C      .F. ---E NO FURTHER FAILURES AFTER MORE THAN ONE REEVALUATION
002155      6052 CONTINUE
002155      MEMB = 1
002156      DO 6055 I=1,6
002160      SLN(I,1) = SGO(I,1)
002162      6055 CONTINUE
002164      6060 CONTINUE
      C
      C STORE STRESS VALUES FOR PRESENT LOADING
002164      DO 6150 I=1,NORP
002166      DO 6150 J=1,NTR
002167      IF(IFAIL(I,J)) GO TO 6150
002172      STORS(I,J) = SGC(I,J)
002176      6150 CONTINUE
      C
002203      IF(INC.EQ.1) GO TO 6500
      C
      C CHECK IF ALL MEMBERS HAVE FAILED
002205      IF(ITOT.GE.KNT) GO TO 7000
      C
      C CHECK FOR FAILED MEMBERS
      C      MEMB = 1 ---E NO FAILURE OR ADDITIONAL FAILURE, INCREMENT IN
      C      STANDARD FASHION
      C      MEMB = 2 ---E FIRST FAILURE, CALCULATE SG* + REEVALUATE
      C      MEMB = 3 ---E FURTHER FAILURES UNDER GIVEN SG*, CONTINUE REEVALUATION
002210      GO TO (6500,6200,915), MEMB
      C
      C CALCULATE SG*, INTERPOLATED LOAD
002217      6200 CONTINUE
002217      IF(INC.EQ.1) GO TO 6500
002221      DO 6250 I=1,6
002223      SLDEL = SLN(I,1)-SLP(I,1)
002225      SGO(I,1) = (SMDEL/SGDEL)*SLDEL + SLP(I,1)
002231      6250 CONTINUE
002233      GO TO 915
      C
      C INCREMENT APPLIED LOAD
002233      6500 CONTINUE
002233      DO 6550 I=1,6
002235      SGO(I,1) = SGO(I,1) + SM(I)
002240      6550 CONTINUE
002241      GO TO 915
002242      7000 CONTINUE
      C
      C CONVERT RADIANS TO DEGREES.
002242      DO 219 I=1,NOR
002244      AL(I)=AL(I)*57.29578
002246      219 CONTINUE
002250      DO 319 I=1,NORP

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```
002252      DO 319 J=1,NTR
002253      BT(I,J)=BT(I,J)*57.29578
002257      319 CONTINUE
002263      GO TO 1

      C
      C
      C
002264      9710 FORMAT (//* MATRIX IS SINGULAR OF RANK = *,I2,
1              *+ DETERMINANT = *,E15.5/)
002264      9715 FORMAT (AE12.5)
002264      9720 FORMAT (//* SOLUTION FOR STRESS CONVERGES IN *,I2,
1              * ITERATIONS*//)

      C
      C
      C
002264      33 STOP
002266      END
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      SUBROUTINE INPUT(NOR,NTR,ICS,IAL,IBT)
C
000010      COMMON /CINPUT/AD,BD,DD,NB,L,EY,EC,A,VMOD,VTI,V,SGM
000010      REAL      NB( 5,30),L( 3,30),IBT( 5,30),IAL( 5)
000010      DIMENSION EY( 5,30),A( 5,30),EC( 5,30),
1          VTI( 5,30),SGM( 5,30)
C
C
000010      WRITE(6,9610) ICS
000015      WRITE(6,9615)
000021      WRITE(6,9620)
000025      WRITE(6,9615)
000031      WRITE(6,9625) AD,BD,DD
000043      WRITE(6,9627) V
000051      WRITE(6,9630) NOR,NTR
000064      WRITE(6,9631) VMOD
000072      WRITE(6,9635)
000076      NORP = NOR + 1
000103      DO 100 I =1,NORP
000104      DO 100 J =1,NTR
000105      IF(I.NE.NORP) WRITE(6,9650) IAL(I),IBT(I,J),NB(I,J),L(I,J),
1          VTI(I,J)
000157      IF(I.EQ.NORP) WRITE(6,9651) IBT(I,J),NB(I,J),L(I,J),
1          VTI(I,J)
000224      100 CONTINUE
000231      WRITE(6,9640)
000235      WRITE(6,9615)
000241      WRITE(6,9645)
000245      DO 150 I =1,NORP
000252      DO 150 J =1,NTR
000253      IF(I.NE.NORP) WRITE(6,9650) IAL(I),IBT(I,J),EY(I,J),EC(I,J),
1          A(I,J),SGM(I,J)
000334      IF(I.EQ.NORP) WRITE(6,9651) IBT(I,J),EY(I,J),EC(I,J),
1          A(I,J),SGM(I,J)
000410      150 CONTINUE
000415      WRITE(6,9680)
000421      WRITE(6,9615)
C
000425      9610 FORMAT (1H1,50X,*SPACE FRAME MODEL*,I2)
000425      9615 FORMAT ( 51X,*-----*)
000425      9620 FORMAT (/51X,*MODEL GEOMETRY*)
000425      9625 FORMAT (/20X,*DIMENSIONS OF MODEL*,10X,*A **E12.5,5X,*R **E12.5,
1          5X,*C **E12.5)
000425      9627 FORMAT (50X,*VOLUME **E12.5)
000425      9630 FORMAT (/20X,*NUMBER OF IMUSS ORIENTATIONS **,I2,
1          /20X,*NUMBER OF FIBER ORIENTATIONS PER TRUSS **,I2)
000425      9631 FORMAT (/20X,*VOLUME FRACTION OF MODEL **,E12.5)
000425      9645 FORMAT (/29X,*ORIENTATIONS* ,20X,*YOUNGIS*,10X,*ECCENT.**,
1          10X,*CROSS**10X,*MAXIMUM*/26X,*TRUSS*,10X,*FIBERS IN*,
2          10X,*MODULUS*,25X,*SECTIONAL*.12X,*STRESS*/43X,*TMUSS*,
3          47X,*AREA*)
000425      9640 FORMAT (/50X,*FIBER PROPERTIES*)
000425      9635 FORMAT (/29X,*ORIENTATIONS*,18X,*NUMBER OF*,7X,*LENGTH OF*,
1          8X,*VOLUME*,

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      2      /26X,*TRUSS*,10X,*FIREHS IN*,13X,*BAYS*,13X,*TRUSS*,
      3      10X,*FRACTION*,
      4      /45X,*TRUSS*/)
000425 9650 FORMAT ( 24X,2(E12.5,2X),4( 5X,E12.5))
000425 9651 FORMAT ( 38X,E12.5,2X, 4( 5X,E12.5))
000425 9680 FORMAT(/50X,*ANALYSIS*)
000425      RETURN
000426      END
```

```

SUBROUTINE RESET(TMPFL,K,IFAIL,SGM,II,JJ,KMAX,IT,MEMB,EPS,MXCAL,
*          ISENT)
000017 COMMON/LOC2/ STO
C
000017 LOGICAL IFAIL( 5,30)
000017 REAL RAT(100),TMPFL( 5,30,40),SGM( 5,30),LARGE*EPS
000017 INTEGER II(40),JJ(40),STO(5,30)
000017 ISENT = 0
C FORM RATIO OF STRESS AT FAILURE TO MAXIMUM STRESS
000020 DO 50 I=1,K
000022 IM=II(I)
000024 JM=JJ(I)
000026 RAT(I)=TMPFL(IM,JM,I)/SGM(IM,JM)
000037 50 CONTINUE
C FIND LARGEST RATIO
000041 CALL MAXVAL(K,RAT,KMAX,LARGE)
C DETERMINE FAILED MEMBERS FOR THIS LOAD
C (I.E. THOSE WITHIN EPS OF MAXIMUM RATIO)
000044 DO 100 I=1,K
000051 IF((LARGE-RAT(I)).GT.EPS) GO TO 100
000057 ITEMP = II(I)
000061 JTEMP = JJ(I)
000063 IFAIL(ITEMP,JTEMP) = .TRUE.
000066 STO(ITEMP,JTEMP)=1
000071 IT = IT + 1
000072 WRITE(6,9720) II(I),JJ(I)
000112 100 CONTINUE
C
C SET REEVALUATION COUNTER = 0 BEFORE INITIAL REEVALUATION
000120 IF(MEMB.EQ.2) KRCAL=0
C RESET SENTINEL ONLY AFTER FIRST REEVALUATION
000123 IF(MEMB.EQ.2) MEMB=3
C SET SENTINEL INDICATING FIRST MEMBER FAILURE UNDER PRESENT LOAD
000125 IF(MEMB.EQ.1) MEMB=2
000130 IF(MEMB.NE.3) RETURN
C LIMIT NUMBER OF REEVALUATIONS PER LOADING BY *MXCAL*
000132 IF (KRCAL.GE.MXCAL) ISENT=1
000137 IF (KRCAL.GE.MXCAL) RETURN
000142 KRCAL = KRCAL + 1
000144 RETURN
000144 9720 FORMAT (10X,*MEMBER FAILURE:*,3X,*TRUSS*,I2,3X,*FIBER*,I2)
000144 END

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SUBROUTINE OUTPSS(NORP,NTR,SGO,SGF,EV)
C
000010 COMMON/LOC2/ STO
000010 REAL SGO(6,1),EV(6,1),SGF( 5,30)
000010 DIMENSION DR(6)
000010 INTEGER STO(5,30)
C
000010 DATA DR/4H 11,4H 22,4H 33,4H 12,4H 23,4H 31/
000010 WRITE(6,9750)
C
000013 AFTER A FIBER FAILS SET THE STRESS TO ZERO,
000020 DO 2 KJ3=1,5
000021 DO 2 KJ4=1,30
000021 IF( STO (KJ3,KJ4). EQ. 0) GO TO 2
000024 SGF(KJ3,KJ4)=0.0
000026 2 CONTINUE
C
000032 SET ALL ELEMENTS OF MATRIX STO TO ZERO.
000034 DO 1 KJ1=1,5
000034 DO 1 KJ2=1,30
000035 1 STO(KJ1,KJ2)=0
000043 DO 100 I=1,6
000045 WRITE(6,9762) DR(I),SGO(I,1),EV(I,1)
000071 100 CONTINUE
000076 IF(NTR.EQ.1) WRITE(6,9769)
000106 IF(NTR.GT.1) WRITE(6,9770)
000117 DO 150 I=1,NORP
000121 DO 150 J=1,NTR,2
000122 JP = J+1
000124 NMJ = NTR-J
000125 IF(NMJ.EQ.0) WRITE(6,9775) I,J,SGF(I,J)
000147 IF(NMJ.GT.0) WRITE(6,9775) I,J,SGF(I,J),I,JP,SGF(I,JP)
000205 150 CONTINUE
C
000212 9750 FORMAT (//20X,*DIRECTION*,20X,*APPLIED LOAD*,20X,*STRAIN*/ )
000212 9762 FORMAT (24X,A4.2(20X,E15.5))
000212 9769 FORMAT (20X,*ORIENTATIONS*,15X,*STRESS*/10X,*TRUSS*,10X,
000212 1 *FIBERS IN*/27X,*TRUSS*/)
000212 9770 FORMAT (2(20X,*ORIENTATIONS*,15X,*STRESS*,5X)/10X,*TRUSS*,10X,
000212 1 *FIBERS IN*,30X,*TRUSS*,10X,*FIBERS IN*/27X,*TRUSS*,
000212 2 50X,*TRUSS*/)
000212 9775 FORMAT (2(12X,I2,I2X,I2,15X,E15.5))
000212 RETURN
000212 END

```



```

      SUBROUTINE COUNP(NORP,NTR,ICON,IT,SGF,SGP)
C
000011      REAL          SGF( 5,30),SGP( 5,30)
000011      DIMENSION      CONMSG(2,2)
000011      DATA CONMSG/10H DOES NOT ,10HCONVERGE ,10H DIVERGES ,
      *          10H          /
000011      ITM = IT-1
000013      WRITE(6,9710) (CONMSG(J,ICON),J=1,4)
000030      WRITE(6,9720)
000034      WRITE(6,9725)
000040      WRITE(6,9726) IT,ITM
000053      DO 100 I=1,NORP
000060      DO 100 J=1,NTR
000061      WRITE(6,9730) I,J,SGF(I,J),SGP(I,J)
000110      100 CONTINUE
000120      9710 FORMAT (//10X,*SOLUTION FOR STRESS *,4A4//)
000120      9720 FORMAT (10X,*TERMINAL STRESS VALUES*)
000120      9725 FORMAT (10X,*TRUSS*,10X,* FIBERS *,10X,2(10X,*S[RESS*]))
000120      9726 FORMAT (56X,2(* (ITER,*,12,* )*,10X))
000120      9730 FORMAT (12X,12,15X,12,15X,2(5X,E12.5))
000120      RETURN
000120      END

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SUBROUTINE MAXVAL(K,Y,KMAX,UPPER)
C
C      DETERMINE MAXIMUM OF ARRAY OF VALUES
C      AND SUBSCRIPT ASSOCIATED WITH MAXIMUM
C
C      PARAMETERS USED
C
C      Y      : ARRAY NAME
C      K      : NUMBER OF ELEMENTS IN ARRAY
C      UPPER  : MAXIMUM VALUE OF Y
C      KMAX   : SUBSCRIPT ASSOCIATED WITH UPPER
C
000007      REAL          Y(K),UPPER
000007      UPPER = Y(1)
000007      KMAX = 1
000010      IF(K.EQ.1) GO TO 150
000012      DO 100 I=2,K
000013      IF(Y(I).LT.UPPER) GO TO 100
000016      UPPER = Y(I)
000017      KMAX = I
000020      100 CONTINUE
000023      150 CONTINUE
000023      RETURN
000024      END

```

		SUBROUTINE MMULD(A,B,C,NROWA,NCOLA,NCOLB,MA,NA,NB)	
	C		
000014		DIMENSION A(NROWA,NCOLA),B(NCOLA,NCOLB),C(NROWA,NCOLB)	R06D0002
000014		REAL A,B,C,X	R06D0003
000014		DO 20 I=1,MA	R06D0004
000015		DO 20 J=1,NB	R06D0005
000016		X=0.	R06D0006
000017		DO 10 K=1,NA	R06D0007
000021	10	X=X+A(I,K)*B(K,J)	R06D0008
000035	20	C(I,J)=X	R06D0009
000047		RETURN	
000047		END	

```

      SUBROUTINE INVRTD(A,NDIM,N,DETA,EPS,IRANK,UNDER)
      C
      C ROUTINE INVRTD INVERTS AN N X N MATRIX USING GAUSS-JORDAN
      C ELIMINATION METHOD
      C
      C * VARIABLE DICTIONARY *
      C
      C A(N,N)          : MATRIX TO BE INVERTED PASSED, INVERSE RETURNED
      C NDIM           : UPPER LIMIT TO MATRIX DIMENSION
      C N              : DIMENSION OF MATRIX
      C IRANK          : RANK OF MATRIX
      C DETA           : DETERMINANT OF MATRIX
      C EPS            : ADJUSTABLE TOLERANCE FACTOR COMPARED TO
      C UNDER          : VALUE OF PIVOTAL ELEMENT DURING INVERSION
      C                : UNDERFLOW LIMIT (CHECK ON COMPUTED VAR.)
      C
      C *****
      C
      000012 DIMENSION A(NDIM,NDIM)
      000012 INTEGER IR(60),IC(60),R,S
      C CHECK MATRIX ELEMENTS FOR UNDERFLOW POSSIBILITIES
      000012 DO 5 I=1,N
      000013 DO 5 J=1,N
      000014 IF(ABS(A(I,J)).LT.UNDER) A(I,J) = 0.0E 00
      000027 5 CONTINUE
      000034 DETA=1.
      000035 SUM=0.
      000036 DO 10 I = 1,N
      000037 DO 10 J = 1,N
      000040 10 SUM=SUM+A(I,J)**2
      000052 SUM=SQRT(SUM)
      000054 DMA = N**2
      000061 RMS=SUM/DMA
      000063 TOL=EPS*RMS
      000064 DO 20 I = 1,N
      000066 IR(I)=0
      000067 20 IC(I)=0
      000072 S=0
      000073 R = N
      000074 30 I=0
      000075 J=0
      000076 TEST=0.0
      000077 DO 50 K = 1,N
      000100 IF(IR(K).NE.0)GO TO50
      000102 DO 40 L = 1,N
      000103 IF(IC(L).NE.0)GO TO40
      000105 X=ABS(A(K,L))
      000112 IF(X.LT.TEST)GO TO40
      000114 I=K
      000116 J=L
      000117 TEST=X
      000120 40 CONTINUE
      000123 50 CONTINUE
      000126 PIV=A(I,J)

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R12D0006
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R12D0010
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R12D0029
R12D0030
R12D0031
R12D0032
R12D0033
R12D0034

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REPRODUCIBILITY OF THE  
 ORIGINAL PAGE IS  
 GUARANTEED

RUN VERSION 2.3 --PSR LEVEL 363--

INVRTD

08/22/74

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000133      IF( ABS(DELTA).LT.UNDER)  DELTA = 0.00E 00
000137      DELTA=PIV*DELTA
000141      IF ( ABS(PIV) .LE. TOL) GO TO 150
000143      IR(I)=J
000145      IC(J)=I
000146      PIV = 1.0E0/PIV
000150      A(I,J)=PIV
000153      DO 60 K = 1,N
000155  60 IF(K.NE.J)A(I,K)=A(I,K)*PIV
000166      DO 90 K = 1,N
000167      IF (K.EQ.I) GO TO 90
000171      PIV1 = A(K,J)
000175  70 DO 80 L = 1,N
000177      IF( ABS(PIV1).LT.UNDER)  PIV1=0.0E 00
000203      IF( ABS(A(I,L)).LT.UNDER)  A(I,L) = 0.00E 00
000217  80 IF(L.NE.J)A(K,L)=A(K,L)-PIV1*A(I,L)
000235  90 CONTINUE
000240      DO 100 K = 1,N
000241  100 IF(K.NE.I)A(K,J)=-PIV*A(K,J)
000253      S=S+1
000254      IF(S.LT.R)GO TO 30
000256  110 DO 140 I = 1,N
000260      K=IC(I)
000262      M=IR(I)
000263      IF(K.EQ.I)GO TO 140
000265      DELTA=-DELTA
000266      DO 120 L = 1,N
000267      TEMP=A(K,L)
000273      A(K,L)=A(I,L)
000302  120 A(I,L)=TEMP
000306      DO 130 L = 1,N
000307      TEMP=A(L,M)
000314      A(L,M)=A(L,I)
000322  130 A(L,I)=TEMP
000330      IC(M)=K
000332      IR(K)=M
000333  140 CONTINUE
000336  150 IRANK=S
000337      RETURN
000340      END

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R12D0035
R12D0036
R12D0037
R12D0038
R12D0039
R12D0040
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R12D0042
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R12D0069
R12D0070
R12D0071

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REPRODUCED FROM  
ORIGINAL DATA